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THESIS

PARTICLE SIZING IN A SOLID-PROPELLANT ROCKET MOTOR USING SCATTERED LIGHT MEASUREMENTS

by

John S. Rosa

December 1985

Thesis Advisor: David W. Netzer

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Particle Sizing in a Solid-Propellant Rocket Motor Using Scattered Light Measurements

by

John S. Rosa
Lieutenant, United States Navy
B.S., United States Naval Academy, 1978

Submitted in partial fulfillment of the
requirements for the degrees of

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ABSTRACT

An experimental investigation was performed to determine, in situ, the change in mean particle size across the exhaust nozzle of a small metallized solid-propellant rocket motor. Light scattering profiles were recorded at both the exhaust and the entrance of the nozzle. The experimental method used provided excellent results within the exhaust. However, combustion light at the wavelength of the transmitted light hampered light scattering measurements within the motor. Particle size measurements were consistent with the sizes found in the collected exhuast products.

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I. INTRODUCTION

The importance of aluminum oxide ($A\ell_2O_3$) particle size produced in solid-propellant rocket motors has been recognized since aluminum was first introduced as a fuel additive. Aluminum added to a propellant will increase the thrust produced and aid in suppressing high-frequency combustion instability. Although the performance improves with aluminum addition, two phase flow losses adversely affect specific impulse efficiency. Specific impulse efficiency is the product of several component efficiencies, i.e., chemical-kinetic, combustion, two-phase flow, two-dimensional flow, submergence and throat erosion. In aluminized propellants, the two-phase flow loss is one of the more significant losses. Two-phase flow losses result from particle-gas thermal and velocity lags. The latter strongly depends on particle size. Parametric studies involving small motors, with throat diameters less than one inch, at AFRPL [Ref. 1] and CSD [Ref. 2] have revealed that a 1 micron change in particle diameter results in a change of 1% in Isp. The effective use of particle damping for suppression of combustion pressure oscillations is also strongly dependent upon the particle size distribution.

One of several analytical computer programs used to predict performance of a solid-propellant rocket motor is the SPP (Solid Performance Program) [Refs. 3,4]. As the above discussion indicates, it is of critical importance to accurately predict particle size. This is especially true for particle damping with minimum smoke propellants which typically contain less than 2% metal by weight. The 1975 version of the SPP [Ref. 3] contains a particle sizing empirical model developed by Cohen. This model was based on correlating collected exhaust samples. After a critical review, this model was considered inadequate. A new model was therefore required for a new SPP version, titled Improved SPP [Ref. 4]. Inorder to meet SPP accuracy goals, this model had to predict particle size within ±10%. Unfortunately, there are no adequate theoretical models relating particle size to propellant and motor parameters. This necessitates the use of empirical methods for correlating particle size.

There are two methods that can be employed to develop an empirical relation. One is to correlate particle size data to propellant and motor variables, as was done by Cohen. The other method is to calculate particle size based on a critical Weber number for a maximum stable drop size [Ref. 5]. After considering the relative merits of each method, Hermsen [Ref. 5] devised an empirical model based on collected particle size data for the improved SPP. This model was correlated to a much broader data base than was previously available to Cohen.

The particle diameter correlated was D_{43}, the mass-weighted diameter, given by:

$$D_{43} = \sum N_i D_i^4 / \sum N_i D_i^3$$

Smith [Ref. 6] has shown that D_{43} was the most appropriate average to use in predicting two-phase flow losses.

Hermsen's empirical relation [Ref. 5] is presented below:

$$D_{43} = 3.6404\ D_t^{.2932}(1 - e^{-.0008163\xi P\tau}) ,$$

where:

D_{43} = mass-weighted average diameter, μ_m

D_t = nozzle throat diameter, in.

ξ = $A\ell_2O_3$ concentration in chamber, g-mol/100 g

P = chamber pressure, psia

τ = average residence time, msec

The predicted D_{43} is now applied to the expression below in order to calculate the two phase flow loss [Ref. 7].

$$\text{ETATP} = C_3(\xi C_4 D_p^{C_5}/P^{.15}\varepsilon^{.08}D_t^{C_6})$$

where:

ETATP = impulse loss effect, %

ξ = mole fraction of condensed species, moles of condensed species per 100 grams of mixture

D_p = D_{43} in microns

P = average motor chamber pressure, psia

ε = nozzle expansion ratio at ignition conditions

D_t = nozzle throat diameter at ignitiion, inches

e = Naperian base 2.71828

$C(\;)$ = coefficients that are a function of D_t and D_p

The two-phase flow loss is applied with the other aforementioned efficiencies to a theoretical Isp. The Isp loss from boundary layer effects is then subtracted from the corrected theoretical Isp to obtain delivered Isp.

Collecting exhaust products is feasible only for small motors and the techniques used often result in variation in the measured size. Validation of the SPP model must be based on data collected within the motor environment. Light scattering measurements are well-suited for this application. These measurements are more easily made if the particles are large compared with the wave length of the transmitted light and the transmittance is greater than 90%. The former allows the accurate application of Fraunhofer diffraction, whereas the latter specification is necessary in order to satisfy single scattering requirements.

The Naval Postgraduate School has conducted a series of investigations to determine the applicability of light scattering measurements to the solid rocket motor exhaust products

[Refs. 8,9,10,11]. This investigation was directed at modifying the apparatus and techniques developed in the previous efforts in order to more accurately determine particle size. Validation of the apparatus was also a goal. The SPP particle prediction model can then be verified by a comparison of the predicted size to the experimental data.

II. THEORETICAL BACKGROUND

The most general theory of light scattering was developed by Mie and is presented by Van de Hulst [Ref. 12]. Mie's theory, although not restrictive in its assumptions in regard to particle size and refractive index, is however very complex to utilize for data reduction. Dobbins, et al. [Ref. 13] and Powell, et al. [Ref. 14] derived similar expressions for intensity ratios at two forward scattering angles based upon an Upper Limit Distribution Function (ULDF). and Fraunhofer diffraction. The ULDF was initially proposed by Mugele and Evans in Reference 15. Although the expressions developed by Dobbins and Powell are extremely useful in relating intensity ratios to D_{32}, the volume-surface mean diameter, these models are still somewhat cumbersome to use for data reduction purposes.

Particle sizes found in solid-propellant rocket motors are often bi-modal. Particles in the larger mode are the most important for two-phase flow loss calculations and are generally much greater in diameter than the wavelength of incident light. Scattering by these large particles is described by Fraunhofer diffraction. Hodkinson [Ref. 16] and others [Refs. 13,14] have demonstrated that diffraction theory (within the forward lobe) can be used to approximate the Mie theory. Buchele in Reference 17 summarized the experimental techniques for determining the particle size by measurements of diffractively scattered light. Buchele presents a function which closely approximates the curves given in References 13 and 14.

$$I(\theta) = \mathrm{EXP}[-(.57\,\alpha\,\theta)^2]$$

where:

$I(\theta)$ = ratio of intensity of scattered light at some angle (θ) to the intensity of scattered light at theta equal to zero degrees

α = $\pi D/\lambda$ is the particle size parameter for diameter D_{32} and wavelength of light lambda (λ).

The above expression was used in the current study for data reduction to obtain D_{32}. Unfortunately, D_{43} is the mean diameter used in the SPP. Therefore, D_{32} must be related to D_{43} either by analyzing exhuast samples or by approximate analytical means.

A final important point is that the above expression is valid for $\alpha \leq 3$ (the center lobe). For the expected ranges of theta and D_{32}, this proves to be a very mild restriction.

III. EXPERIMENTAL APPARATUS

A. ROCKET MOTOR

The rocket motor used in this investigation was the same as the long motor described in Reference 11. The motor components are presented in a photograph in Figure 3.1 and the installed motor is shown in Figure 3.2. A schematic is also presented in Figure 3.3. The propellant grain dimensions remained the same as in the previous effort [Ref. 11]. The grain was two inches in diameter, one inch in length and had a web thickness of .725 inches. The grain was cylindrically perforated and allowed to burn also on the aft end. The igniter was composed of $BKNO_3$. Ignitiion of the igniter was achieved by heating a resistance wire with a 12 VDC source.

Some of the exhaust products were collected in an eight inch diameter stainless steel exhaust tube. The products were collected from both the side walls of the tube and the end cap. Another particle sample was collected from the walls of the combustor, near the nozzle entrance. Both samples were then cleaned and mounted for observation using a scanning electron microscope.

B. LIGHT SCATTERING APPARATUS

The apparatus shown in Figures 3.4 and 3.5 was basically the same as used in Reference 11 with some exceptions. The light source used for the nozzle exhaust was a 8-miliwatt, helium-neon laser. The nozzle entrance also used a 8-milliwatt helium-neon laser. The lasers were mounted on two parallel optics benches, such that one beam could pass through the exhaust and the other beam could pass through the motor cavity adjacent to the nozzle entrance. A beam expander/collimator was used with the helium-neon laser in the exhaust. Each beam was intercepted by a stop placed directly in front of the narrow pass filter. The narrow pass filter was used to eliminate extraneous light. The stop and narrow pass filter were placed 30.5 centimeters from the motor centerline for the exhaust beam and 11.5 centimeters from the motor centerline for the motor cavity beam. The exhaust beam narrow pass filter had a diameter of 5.08 centimeters and the motor cavity narrow pass filter had a diameter of 2.3 centimeters. Both beams passed through the centers of these filters. In the present arrangement of the apparatus this resulted in a maximum angle for collecting scattered light of 4.8 degrees in the exhaust and 6.0 degrees in the motor cavity. The placement of the optics closer to the motor centerline allowed for a greater maximum angle to be recorded than in the original design. Directly following the narrow pass filters were condensing lenses. Both paths used a lens with a diameter of 5.08 centimeters. These lenses had a focal length of 50 centimeters and were utilized to focus scattered light onto a linear array of photodiodes. The array consisted of 1024 silicon photodiodes with .025 millimeter spacing. The apparatus in Reference 11 positioned the lenses such that only angles from 0 to .04 radians could be observed. In actuality, however (as a consequence of diffraction around the beam stop and beam spreading), the range of useful angles where only scattered light occurred was from .02 radians to .04 radians. In the current arrangement the diode array was placed 1.0 centimeters below the main beam and the collecting tube diameter was enlarged. This allowed a range of angles from .02 to .07 radians to be observed.

C. DATA ACQUISITION AND DATA REDUCTION

The data acquisition system is presented in detail in Reference 10. The system controller was an HP 9836S computer and the HP 6942A multiprogrammer provided A/D conversion and storage. The data acquisition system was programmed to take data at a specified point in the motor firing by inputing a trigger pressure and a time delay after the trigger pressure was reached. The number of diode scans for the exhaust and motor cavity were eight and four respectively (limited by the current data acquisition system memory size).

Two methods were used in References 10 and 11 for data reduction, one of which was altered for this study. The modified method pertained to the iterative graphics technique. In References 10 and 11 the experimental data were normalized and compared to a theoretical profile that was also normalized to some assumed scattered light intensity at zero degrees for a specified D_{32}. A "best-fit" of the experimental profile to the theoretical one yielded D_{32}. The current investigation determined that this method resulted in ambiguity in determining D_{32} as a consequence of assuming a centerline intensity for the scattering profile. The method used in the present study was one in which the experimental data were not altered. A theoretical curve was generated for any specified value of D_{32} based upon a selected initial angle (θ_1) and the corresponding intensity at that angle (I_1) from the unaltered experimental data. The approximate intensity profile for a polydispersion given by Reference 17 is:

$$I_2 = I_1 \mathrm{EXP}-\{(\theta_2^2 - \theta_1^2)(.57\ D\pi/\lambda)^2\}$$

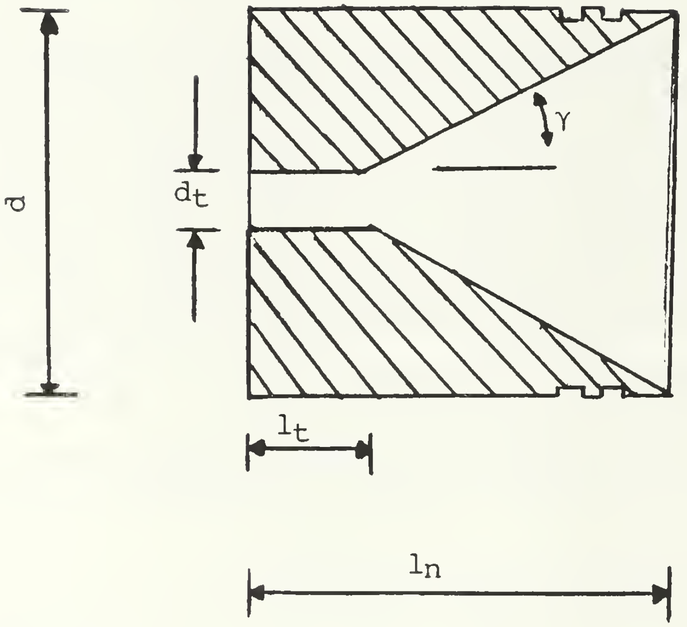
Specification of a series of values for θ_2 results in values for I_2 and, therefore, an I vs θ theoretical profile that passes through the experimental data at I_1, θ_1. If this curve does not fit the experimental data, then other values of D_{32} can be chosen and a new theoretical curve generated. A "best-fit" method is subsequently used to determine D_{32}. In summary, the method used for obtaining the mean particle size is based upon fitting an approximate (although quite accurate within specific angle restrictions) theoretical profile for a polydispersion to the unaltered profile obtained experimentally over a small range of scattering angles. The modified data reduction program is presented in the Appendix.

The second method was similar to the first and also used the above expression solved for D_{32}:

$$D_{32}^2 = -\mathrm{Ln}(I_2/I_1)(\lambda/.57\pi)^2/(\theta_2^2 - \theta_1^2)$$

The procedure used was to first select a starting angle, θ_1, along with a θ_2/θ_1 ratio. A value of I_2 at θ_2 was obtained from the experimental data. This was repeated with increasing values of θ_2 and then again with different values of θ_2/θ_1. The results were plotted graphically as particle size vs scattering angle for each angle ratio. A nearly constant value of D_{32} vs θ indicated a good correlation.

TABLE I



Description	Copper Nozzle	Copper Nozzle
Outside Diameter (d, inch)	2.125	2.125
Length (ln, inch)	1.25	1.25
Throat Diameter (dt, inch)	.28	.23
Slope (converging) Angle (γ, degree)	45	45

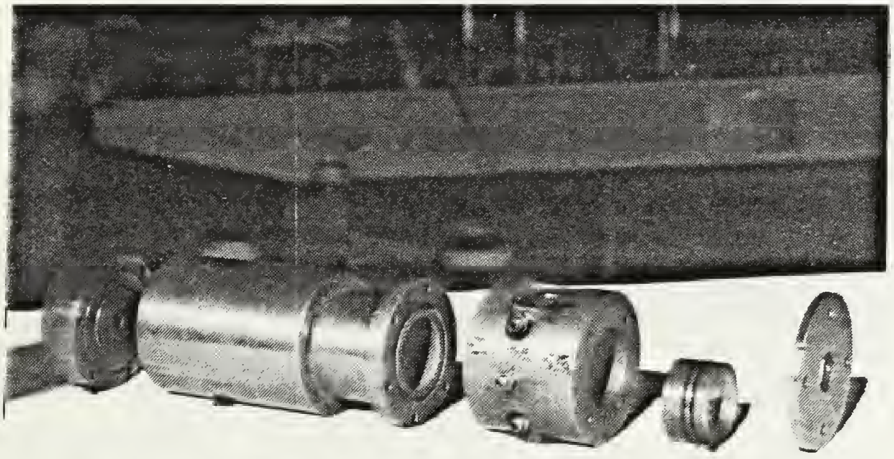


Figure 3.1. Motor Components

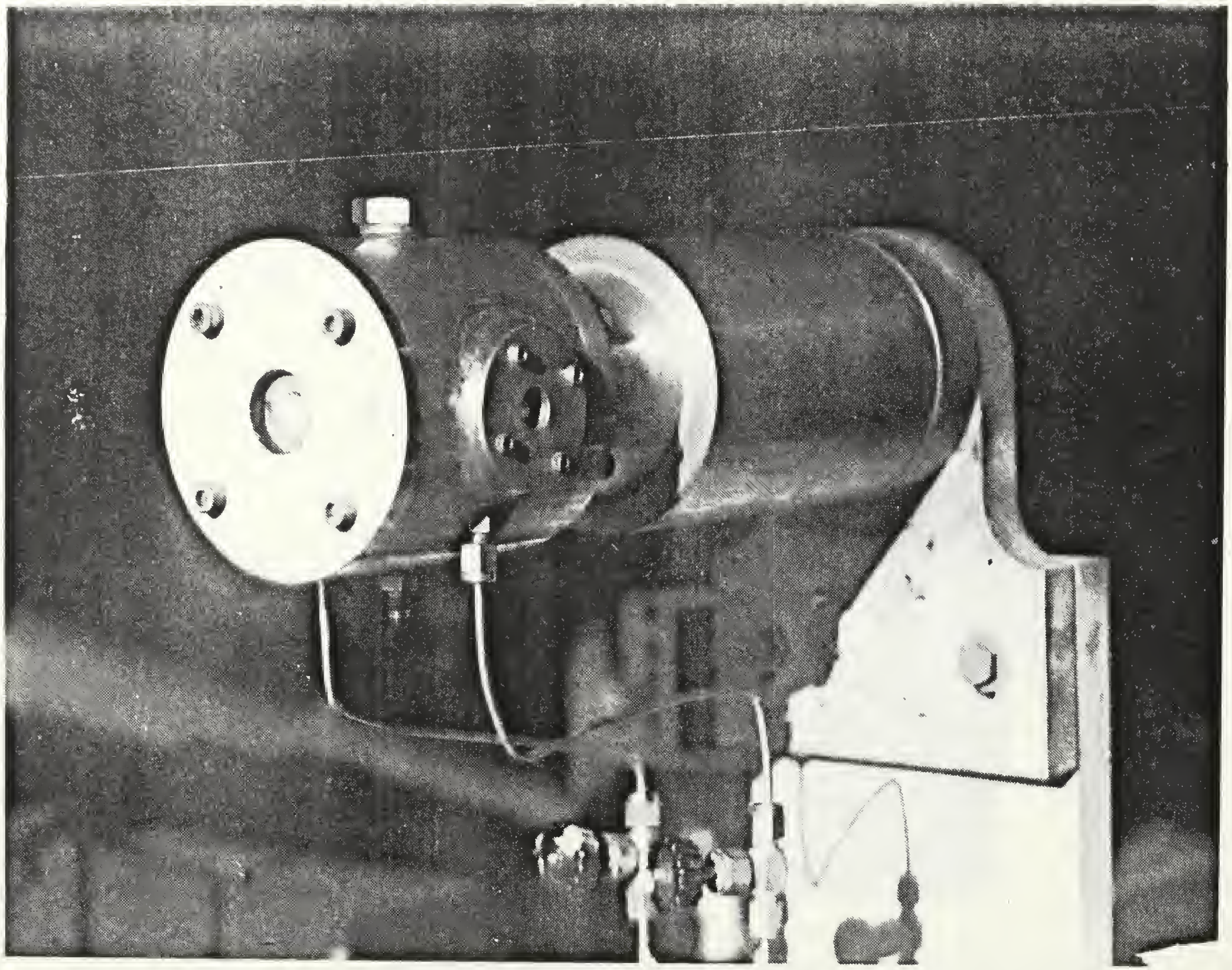
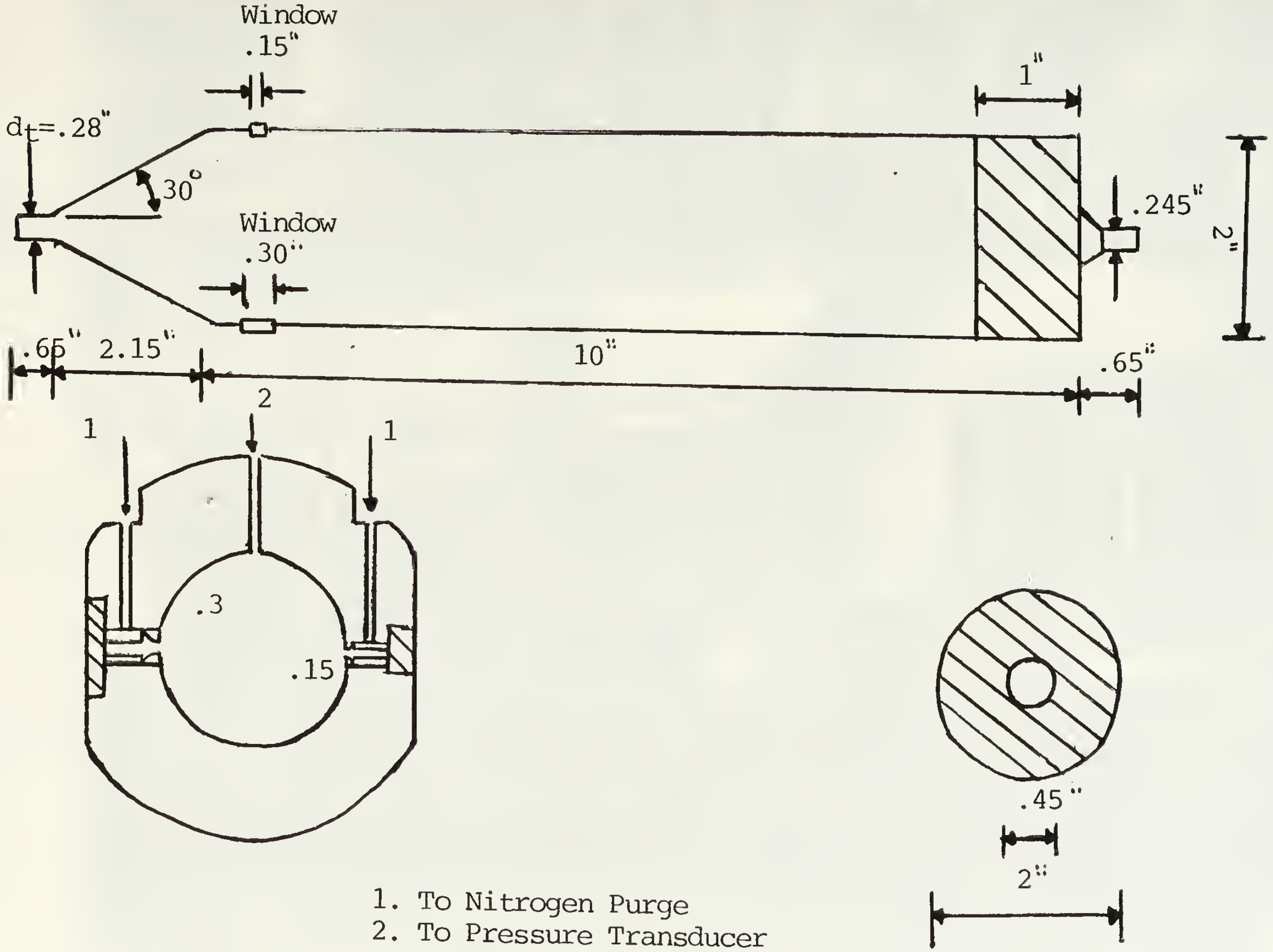


Figure 3.2. Installation of Rocket Motor



1. To Nitrogen Purge
2. To Pressure Transducer

Figure 3.3. Schematic of the Motor

ENLARGE

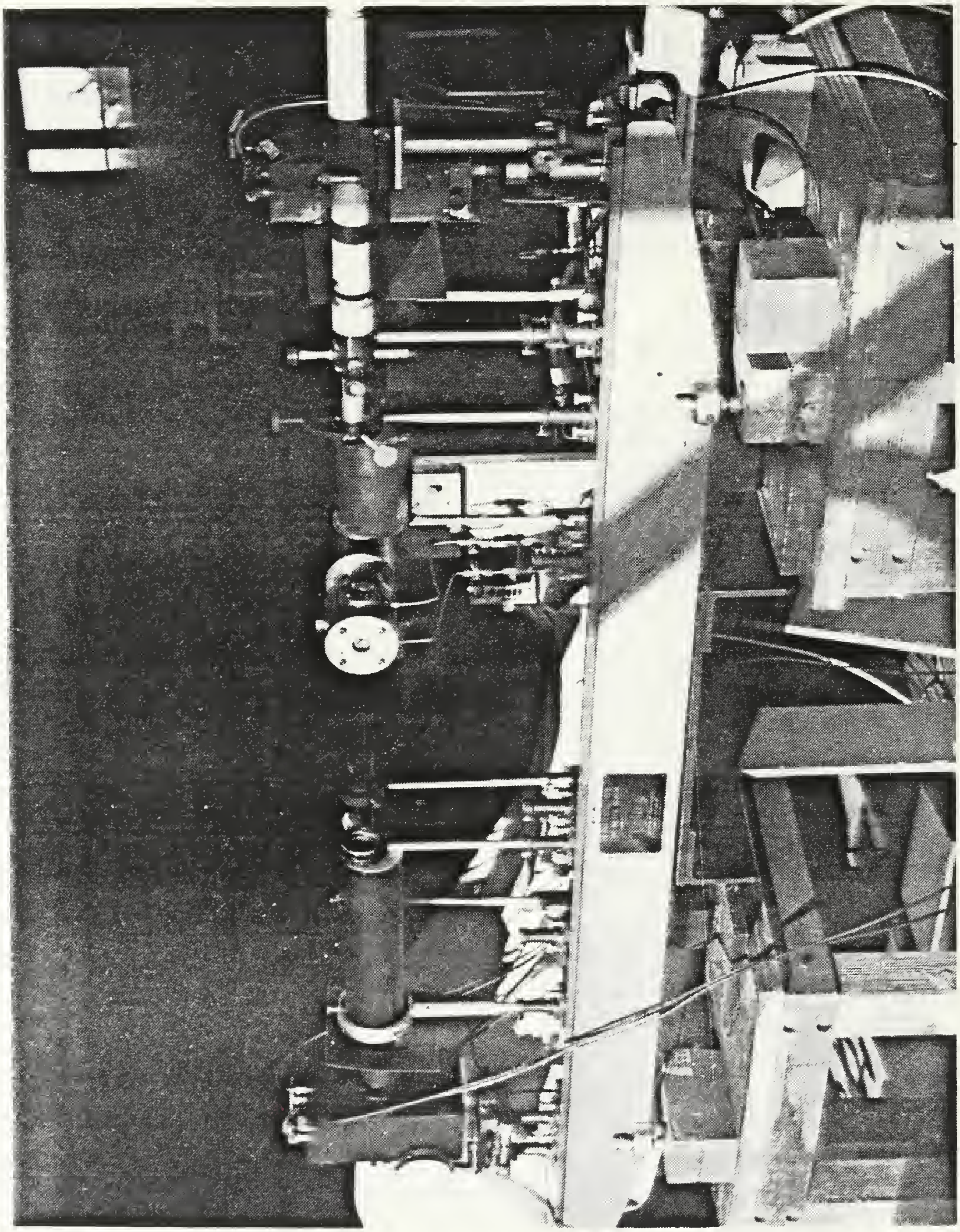


Figure 3.4. Light Scattering Apparatus

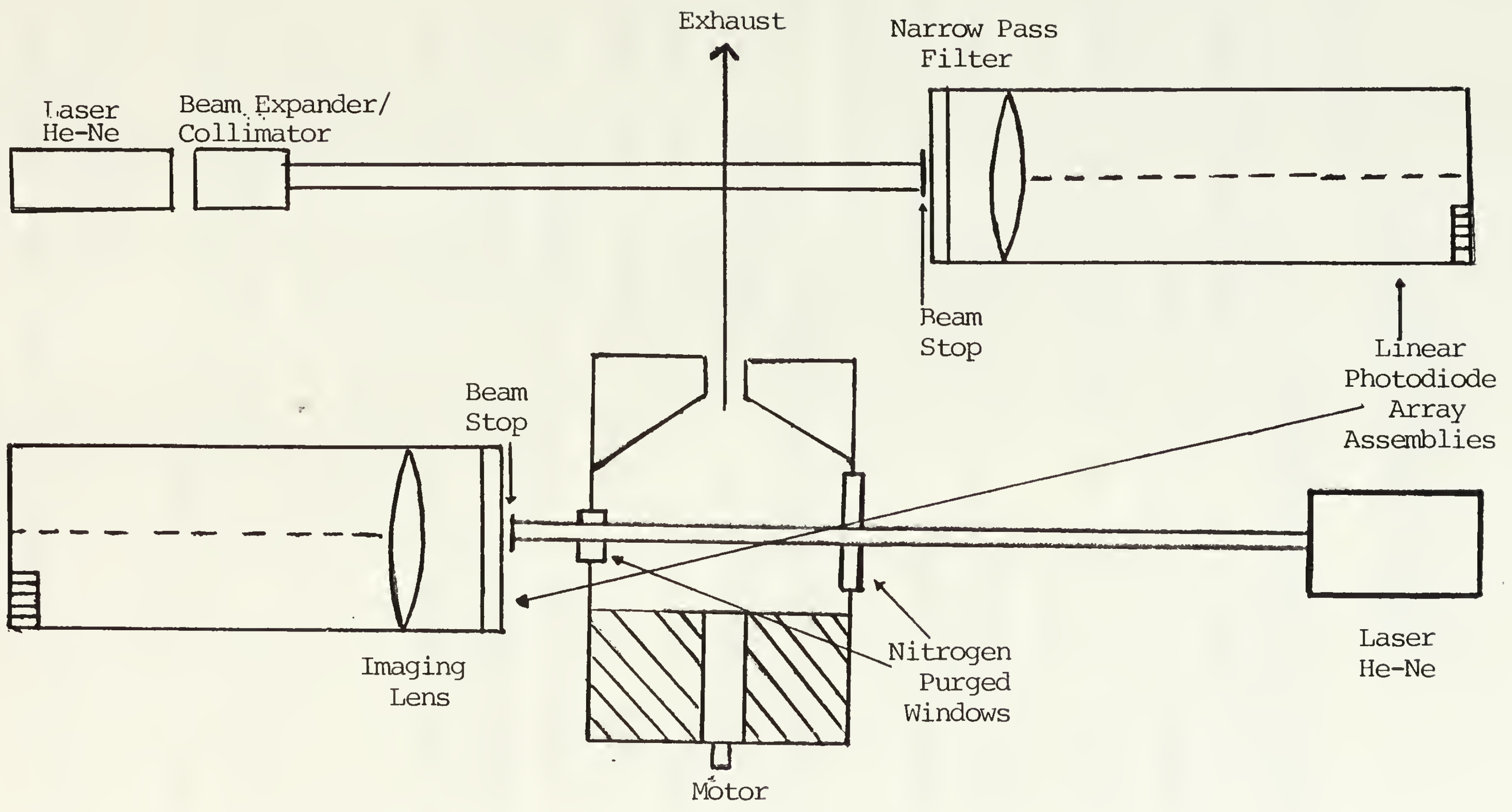


Figure 3.5. Schematic Diagram of Light Scattering Apparatus

TABLE II

LIGHT SOURCE SPECIFICATION

A. Helium-Neon Laser (Exhaust)

1. Manufacturer Spectra-Physics
2. Model: 147
3. Type: He-Ne Class IIIB
4. Output Power: 8 mWatt
5. Beam Diameter: .92 mm
6. Beam Divergence: .87 nrad.

B. Helium-Neon Laser (Motor Cavity)

1. Manufacturer: Uni-Phase
2. Model: 1305P
3. Type: He-Ne Class IIIB
4. Output Power: 5 mWatt
5. Beam Diameter: .81 mm
6. Beam Divergence: 1.00 mrad.

IV. RESULT AND DISCUSSION

A. INTRODUCTION

The purpose of this study was to improve and validate the accuracy of the apparatus used for particle sizing in the rocket motor environment. Also, the experimental data will provide a basis to verify the particle size prediction model of the SPP.

The apparatus had been calibrated by Harris [Ref. 10] and Kertadidjaja [Ref. 11] using glass and polystyrene spheres in a suspension of water. Kertadidjaja [Ref. 11] also attempted to demonstrate the applicability of the apparatus to the combustion environment. This investigation continued the earlier studies with several refinements. Three propellant types were used in this investigation. All three utilized a GAP binder with ammonium perchorate (AP) oxidizer. Each had varied aluminum content, with the percentages present being 0%, 2%, and 4.8%. The size of the aluminum powder was 20 microns. The major ingredient compositions for the 4.8% aluminized propellant were 14.7% GAP, 45.7% 200 μm AP, 24.6% 25 μm AP, 8.5% TEGIN and 4.8% 20 μm $A\ell$. The 0% and 2% aluminized propellants kept the same solids loading.

B. SYSTEM CALIBRATION

As previously mentioned, the apparatus was calibrated by both Harris [Ref. 10] and Kertadidjaja [Ref. 11]. The apparatus was re-calibrated in this study as a result of the modifications that were made. The standard calibration procedure described in detail by Harris [Ref. 10] remained the same. The laser beam passed through a glass container holding a suspension of polystyrene spheres and water and was initially positioned on the number one diode. The linear diode array was then moved vertically down, with the aid of a dial indicator, such that the number one diode was one centimeter below the main beam. Since the diode array was 2.56 centimeters long and was 50 centimeters from the focusing lens, this arrangement allowed for a range of measuring angles from .02 to .07 radians. Therefore, the scattered light striking the diodes would not be affected by the main transmitted beam or the light diffracted by the beam stop as in the previous two studies. This arrangement was used both for the exhaust beam and the motor cavity beam.

Two polydispersion samples of polystyrene spheres, with D_{32}'s of 4.8 microns and 10.2 microns, were used for the calibration. These samples were chosen because the D_{32} was known and the expected D_{32} of the actual aluminum oxide particles during a motor firing was between 1 and 15 microns. The results are presented in Figures 4.1, 4.2, 4.3 and 4.4. These results were encouraging in regards to validating the modifications and the method for data reduction. Calibrations were also conducted within the motor cavity with the laser beam and scattered light passing through the motor windows. Figures

4.1 and 4.2 are representative of the results obtained. This indicated that the motor windows did not adversely affect scattering profile and, therefore, bias the results.

An initial point of concern was the narrow range of measuring angles which were employed in the present apparatus. Since large particles diffract most of the incident light at small angles and very small particles diffract most of the incident light at large angles, the range and minimum angle employed could not have resulted in sufficient sensitivity to particle size for the expected range of particle sizes. Also shown in Figure 4.1 are two additional theoretical profiles for D_{32} of 10 and 8.3 microns. It was apparent from the sensitivity of the slope change with D_{32} that the mean particle size could be determined with an uncertainty less than ±.5 microns.

The "upsweeps" in the curves at larger angles using the two angle method were the result of the increase in slope of the scattering profile due to the effect of truncation by the apparatus. These parts of the curves remain only to provide a reference to the angle ratios.

Another informative point in apparatus design is given by Hirleman [Ref. 18] in regards to placement of the focusing lens. Hirleman notes that truncation of the larger scattering anbles, which is a function of the placement of focusing lens, will cause a biasing against the small particles. The expression given in this discussion is:

$$Z_c = (\pi d/7.66\lambda)D$$

where:

Z_c = critical distance in front of the focusing lens where significant energy diffracted by particles less than diameter D is truncated by the focusing lens

λ = wavelength of the incident light

For a given Z_c, all particles that are greater than D in size will have 84 percent of their diffracted energy pass through the focusing lens. In the exhaust configuration of the present apparatus Z_c was equal to 30.5 centimeters, d was 5.08 centimeters and λ was .6328 microns. This yields a D of 9 microns. Thus, according to this criterion, some of the scattered light from particles below 9 microns is truncated and, therefore, results in a bias towards larger particles. This type of biasing was small in the present apparatus down to particle sizes of approximately 3 microns (the smallest particles in the 4.8 micron D_{32} polydispersion) as evidenced by the good calibration results is shown in Figure 4.3. However, the apparatus could be improved by either moving the lens closer to the exhaust (at the risk of apparatus damage from the exhaust jet) or by using a larger diameter lens.

Transmittance effects were also investigated in conjunction with the calibration. As previously mentioned, transmittances above 90% are required to meet single scattering requirements. Calibrations were conducted using polystyrene spheres with a D_{32} of 10.2 microns. Scattering data were recorded for transmittances of 85%, 70%, 60%, 50%, and 30%. The results are presented in Figures 4.5 through 4.14, and summarized in Table III. Both the curve fit and the two-angle methods resulted in very good agreement with the actual mean particle size with transmittances as low as 50%. Even a transmittance of 30% did not severely affect the measurement. These results indicate that particle sizing methods based upon single scattering theory can effectively be used in a multiple scattering environment with transmittances significantly less than 90%.

A test was then conducted to determine the transmittance in the actual motor exhaust using the 2% aluminized propellant. The procedure was the same as the one used in Reference 11. The transmitted beam was directed onto the diode array (with the appropriate filters to reduce the intensity) and the beam profile was recorded. The motor was then fired and the profile was again recorded. The results are presented in Figure 4.15. The results indicated a transmittance greater than 90%, with some beam spreading. There was also no apparent beam shift. Therefore, transmittance loss was determined not to be a debilitating factor in the motor exhaust jet.

The calibration curves have an apparent limit of approximately .04 radians for which scattered light can be recorded (for example, see Figure 4.3). However, it was stated that the apparatus was designed to record angles up to .07 radians.

This is due to the water-glass interface having an effective index of refraction of 1.39. Thus, the scattering angles are corrected for this high index of refraction, resulting in a corrected maximum angle of approximately .04 radians.

C. NOZZLE EXHAUST MEASUREMENTS

One test was conducted with a nonmetallized propellant. The results, presented in Figure 4.16, show no scattering. Therefore, the scattering observed by Kertadidjaja [Ref. 11] at smaller angles for a similar test was probably the result of beam broadening and diffraction around the beam stop.

Three tests were conducted with both the 4.8% and 2% aluminized propellants. The motor firing data and a summary of the particle size measurements are presented, respectively, in Tables IV and V. From light scattering measurements each propellant showed a similar result, one test with a D_{32} of approximately 5 microns and one with a larger value of D_{32} (7-12 microns). This test-to-test variation probably resulted from the very short burn times and the corresponding lack of a well-defined steady-state condition. These results are presented in Figures 4.17 through 4.28. Typical S.E.M. photographs are shown in Figure 4.29. The light scattering results were quite consistent with those obtained from the S.E.M. evaluation. Although the sample sizes from which the S.E.M. evaluations were based were relatively small (see Table VI), it still provided a good indication as to the validity of the light scattering measurements. It should be noted that D_{32}, and to an even greater extent D_{43}, is strongly dominated by the larger particles. One or two large particles can significantly change D_{32}. Future S.E.M. evaluations should utilize much larger sample sizes.

The SPP equation for D_{43} (which is primarily a function of throat diameter) predicted much smaller values of D_{43} than observed in this limited set of data. The SPP model, however, is based on particulate data from motors with nozzle diameters greater than 1 inch.

D. NOZZLE ENTRANCE MEASUREMENTS

Light scattering measurements through the motor at the nozzle entrance were unsuccessful as a result of combustion light existing at the same frequency as the laser light. This was the case for both the helium-neon laser ($\lambda = .6328\ \mu m$) and the argon laser ($\lambda = .488\ \mu m$).

The analyses of the S.E.M. data for the nozzle entrance indicated a much larger D_{32} and D_{43} as compared to the nozzle exit measurements. Therefore, a significant reduction in size appears to have occurred to the larger particles across the exhaust nozzle.

TABLE III

EFFECT OF TRANSMITTANCE ON MEASURED PARTICLE SIZE

(D_{32} from Manufacturers Data Equals 10.2)

Transmittance (%)	Measured D_{32} (microns)
85	9.8
70	9.6
60	9.5
50	9.4
30	9.3

TABLE IV

SUMMARY OF MOTOR FIRINGS

Date of Test	Wt of Alum (%)	Press P_c (psig)	Press Max P_c (psig)	Burn Time (sec)	Residence Time (msec)	D_t (in.)
Oct 31, 85	0	350	366	3.8	-	.28
Oct 22, 85	4.8	312	328	2.9	10.9	.28
Oct 23, 85	4.8	328	359	2.8	11.3	.28
Oct 18, 85	4.8	333	340	2.8	11.3	.28
Nov 19, 85	4.8	450	466	.95	14.0	.25
Oct 30, 85	2.0	296	296	2.8	10.4	.28
Nov 26, 85	2.0	408	467	2.0	14.4	.28
Nov 25, 85	2.0	566	575	1.8	16.7	.25

Note: Pressure colume labeled P_c indicates pressure at which data was taken.

TABLE V

SUMMARY OF EXPERIMENTAL RESULTS

Wt of Alum (%)	Press P_C (psig)	D_{32} Light Sct. (psig)	D_{32} S.E.M. Ext./Mtr.	D_{43} S.E.M. Ext./Mtr.	D_{43} SPP Model
4.8	328	5.6	5.6/18.2	7.3/24.7	2.3
4.8	333	5.5	- / -	- / -	2.3
4.8	450	12.0	13.6/18.9	19.7/23.9	2.5
2.0	296	7.0	12.2/14.4	18.6/19.6	2.3
2.0	408	9.3	- / -	- / -	2.3
2.0	566	4.6	4.9/10.8	6.0/13.2	2.5

Note: (-) indicates sample was not taken for this run.
Diameters are in microns.

TABLE VI

S.E.M. PARTICLE DISTRIBUTION

	Size in microns															
	1	2	3	4	5	6	7	8	9	10	12	15	19	20	25	30
Oct 23 Ext.	53	22	16	11	7	4	2	1			1					
Oct. 23 Mtr.	50	21	22	13	9	6	8	4	1	2	1	1			1	2
Oct. 30 Ext.	45	42	11	13	21		2	2		1	1		1		1	
Oct. 30 Mtr.	24	15	3	6	28	3	7	13		6		3	1	2		1
Nov. 19 Ext.	64	35	31	7	6	1	1	1		2	1			1	1	
Nov. 19 Mtr.	73	29	9	5	12	4	1	1	1	2	1	1	1		2	1
Nov. 25 Ext.	44	39	22	3	14	4	1	1		1						
Nov. 25 Mtr.	37	30	11	1	15	8	3	8		3	4	3		1		

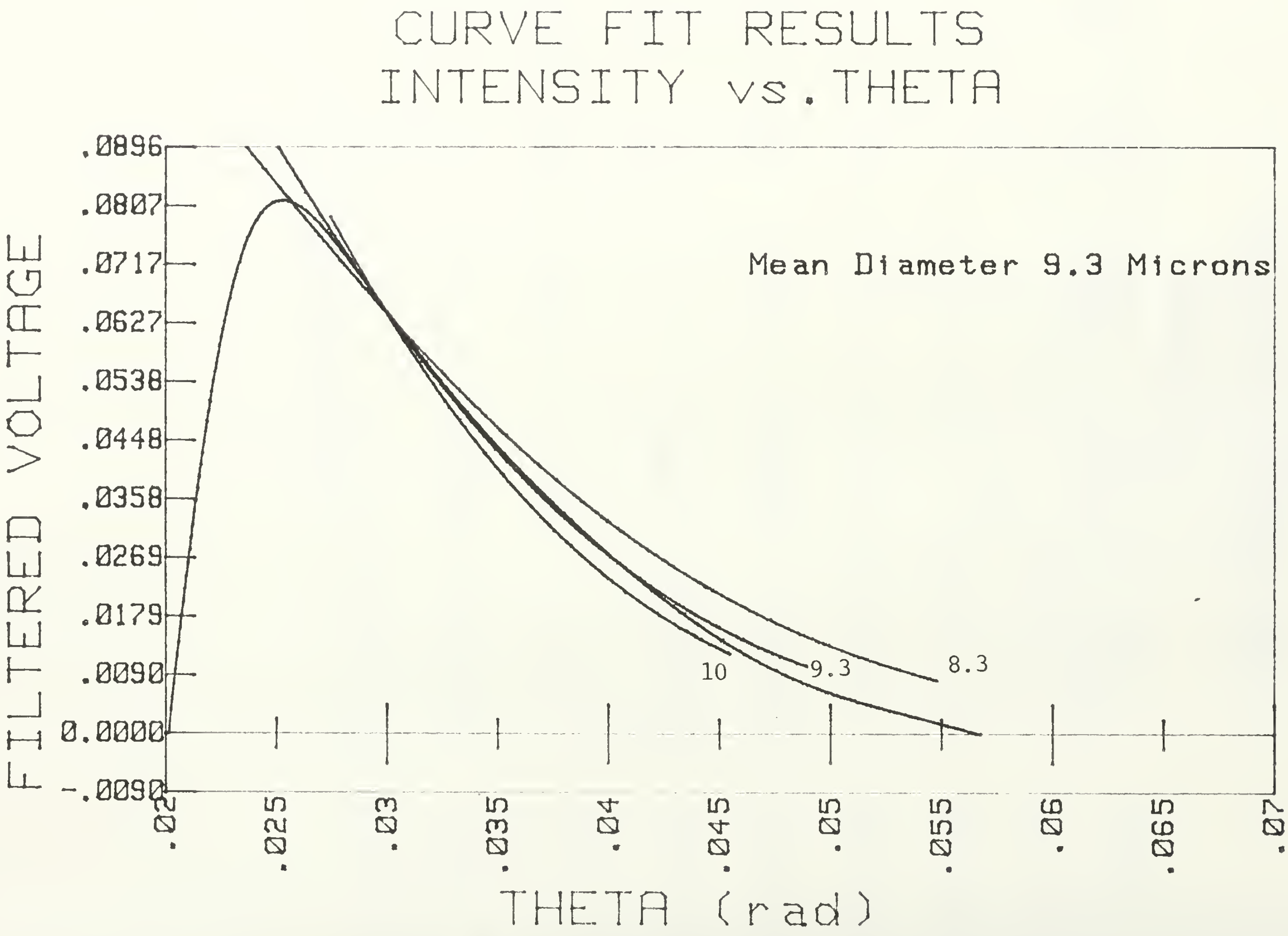


Figure 4.1 Calibration With 10.2 Micron Polystyrene Spheres

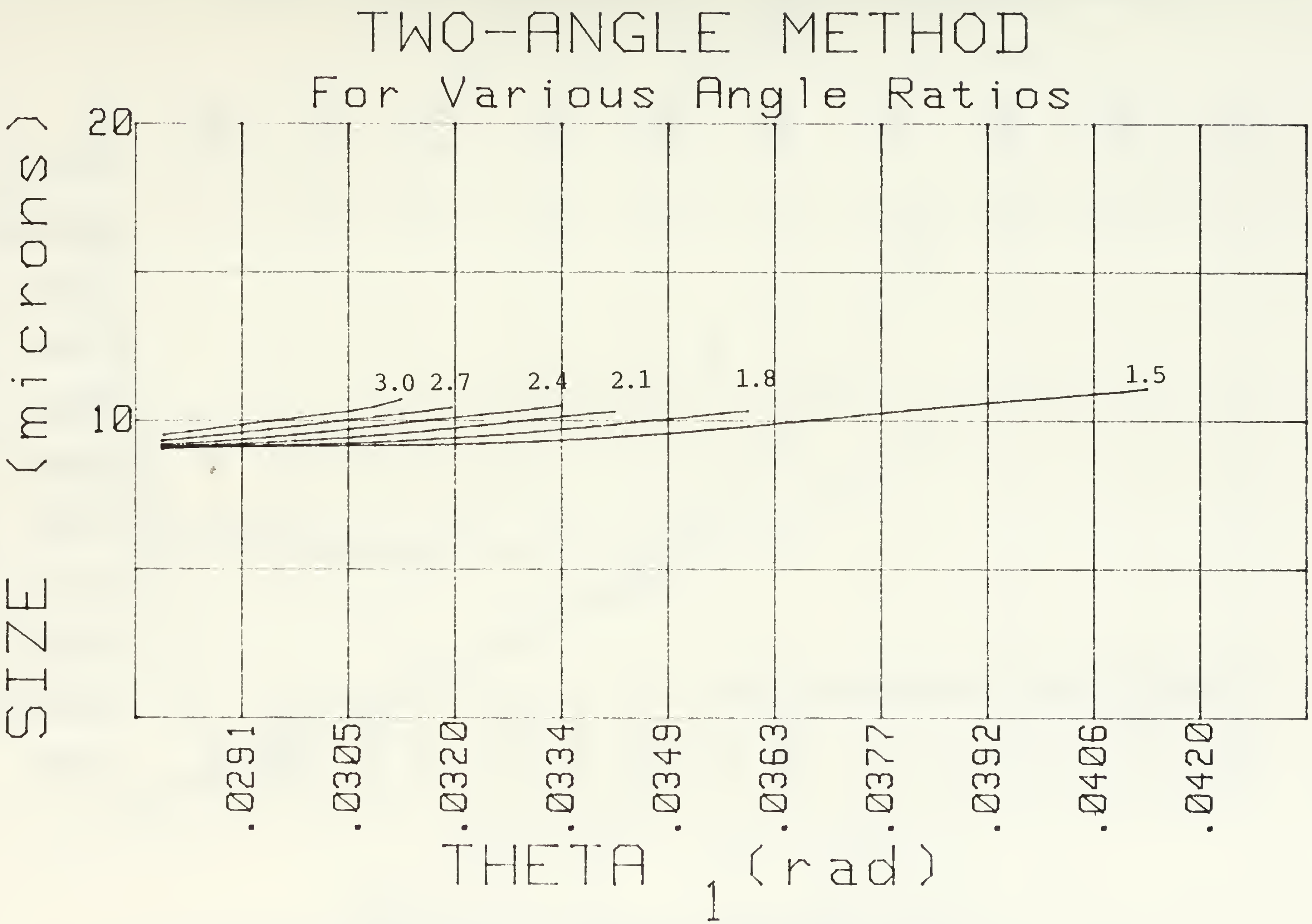


Figure 4.2 Calibration With 10.2 Micron Polystyrene Spheres

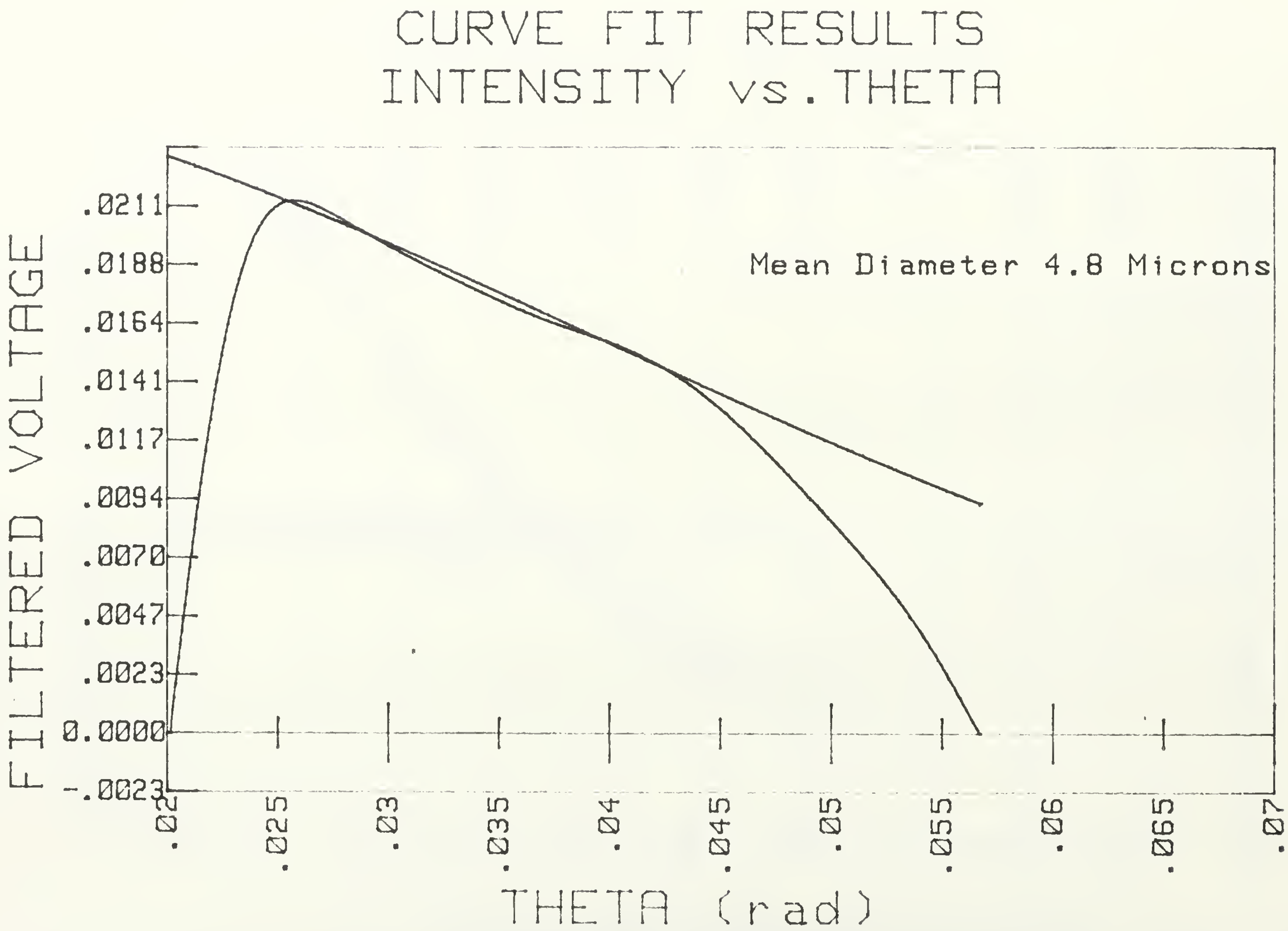


Figure 4.3 Calibration With 4.8 Micron Polystyrene Spheres

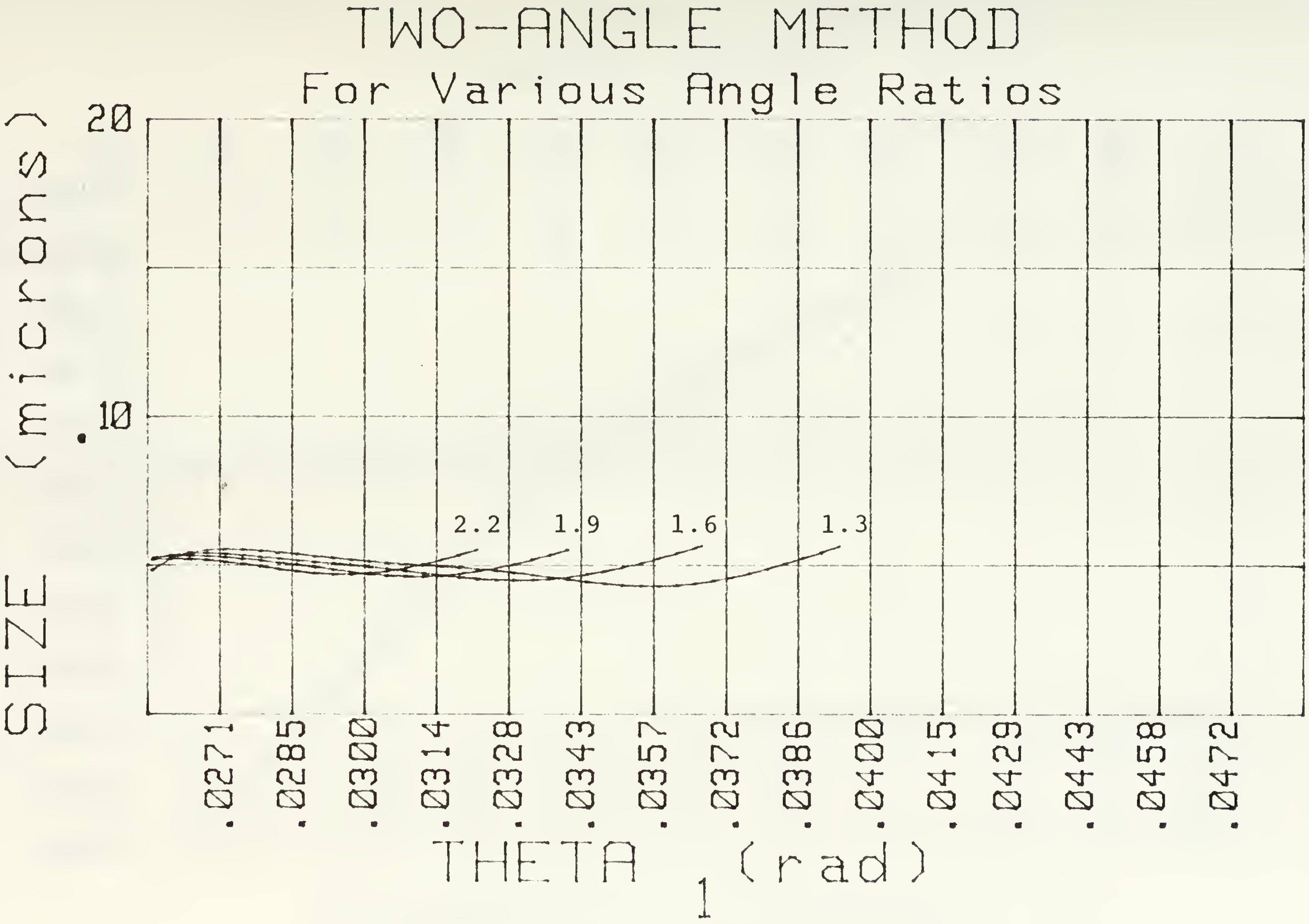


Figure 4.4 Calibration With 4.8 Micron Polystyrene Spheres

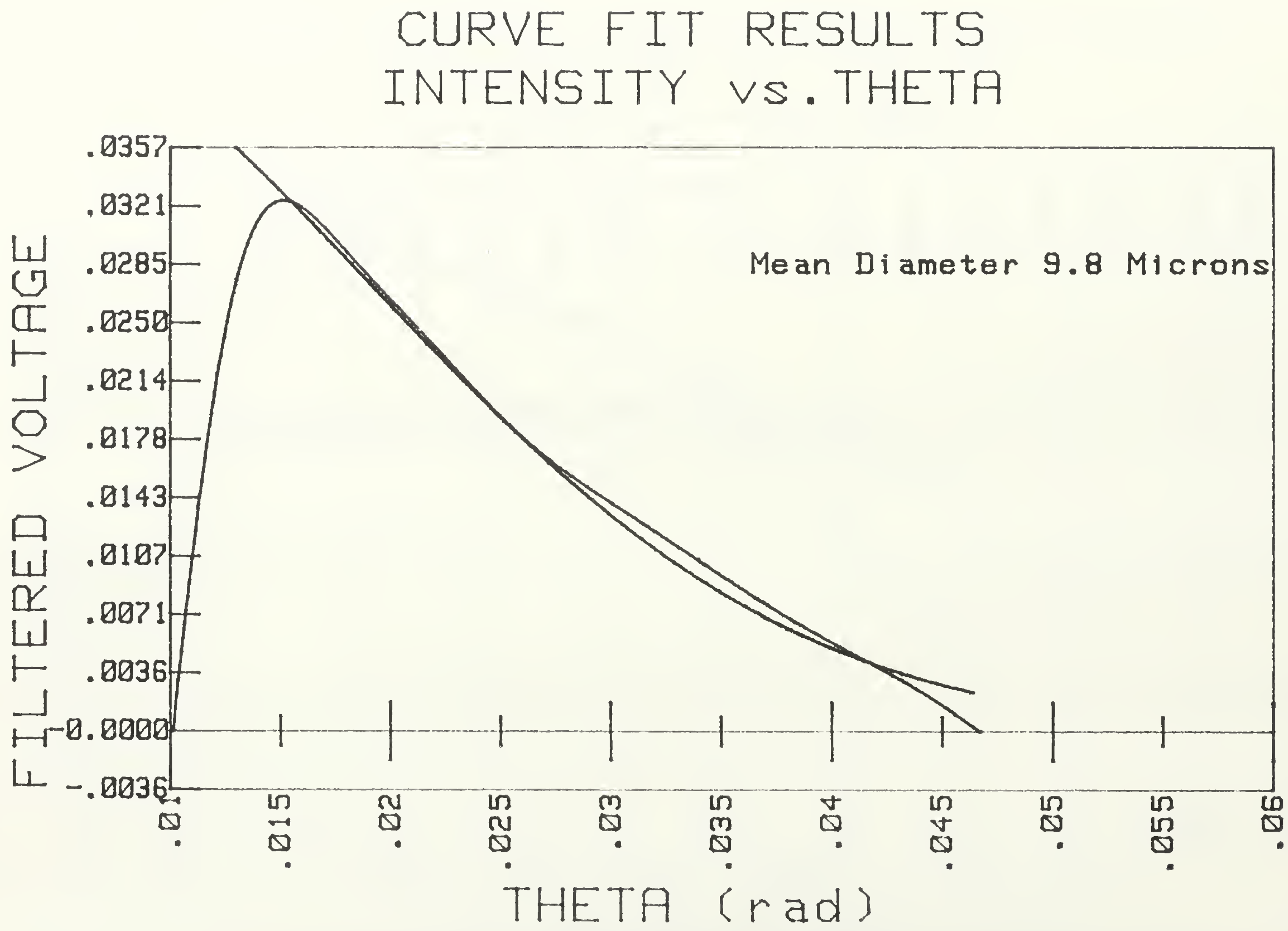


Figure 4.5 Curve Fit Method, 85% Transmitted Light

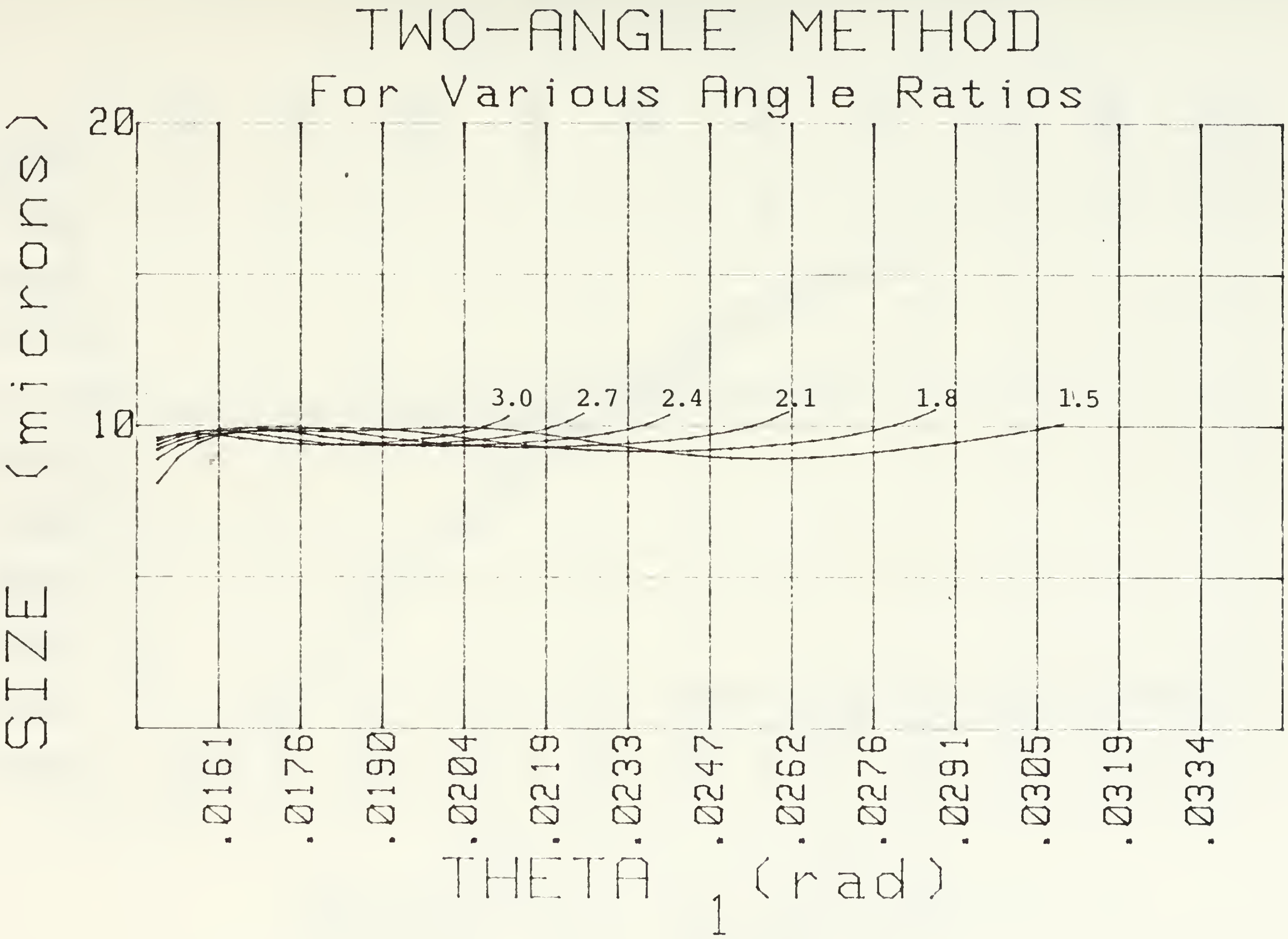


Figure 4.6 Two Angle Method, 85% Transmitted Light

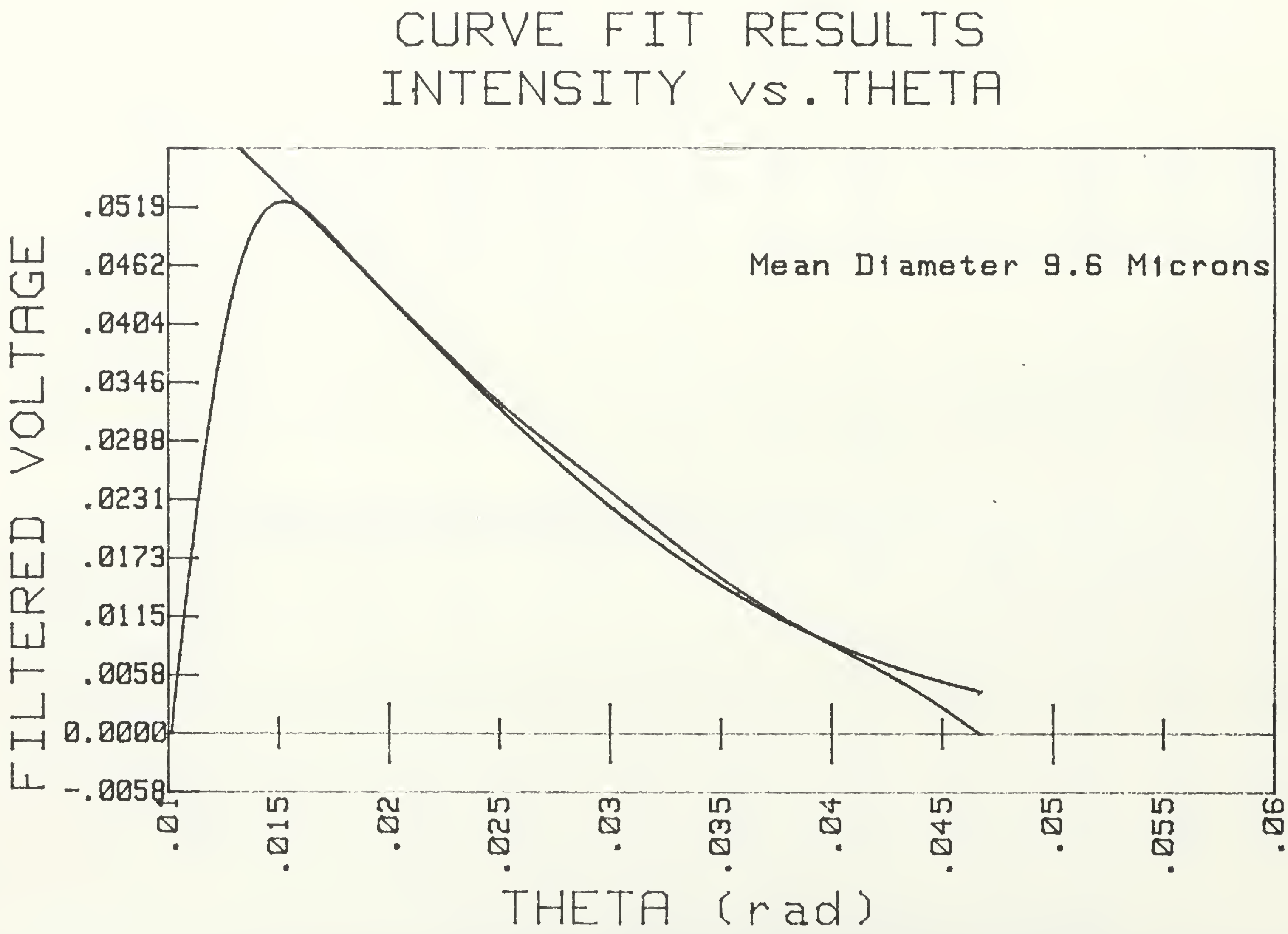


Figure 4.7 Curve Fit Method, 70% Transmitted Light

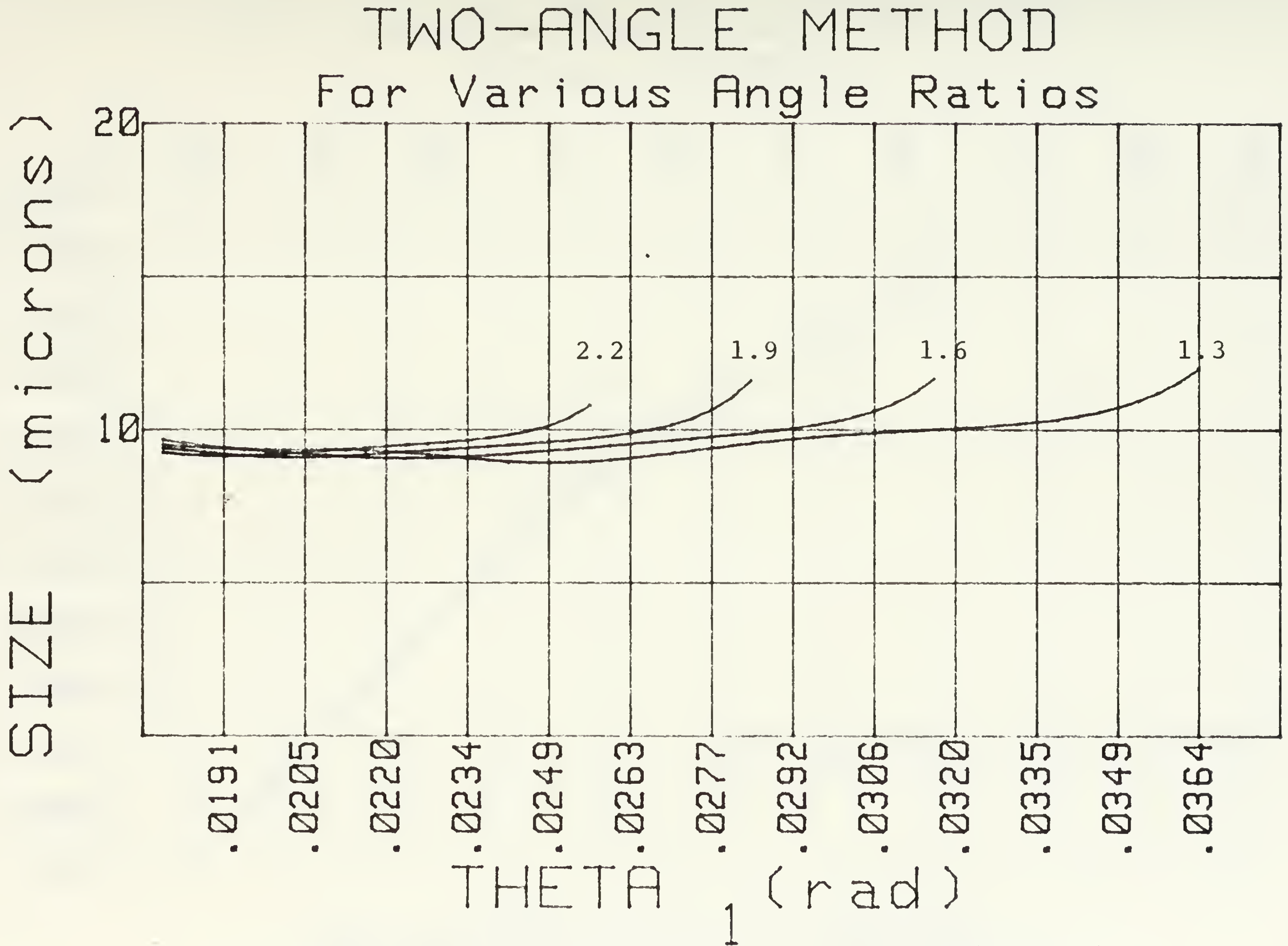


Figure 4.8 Two Angle Method, 70% Transmitted Light

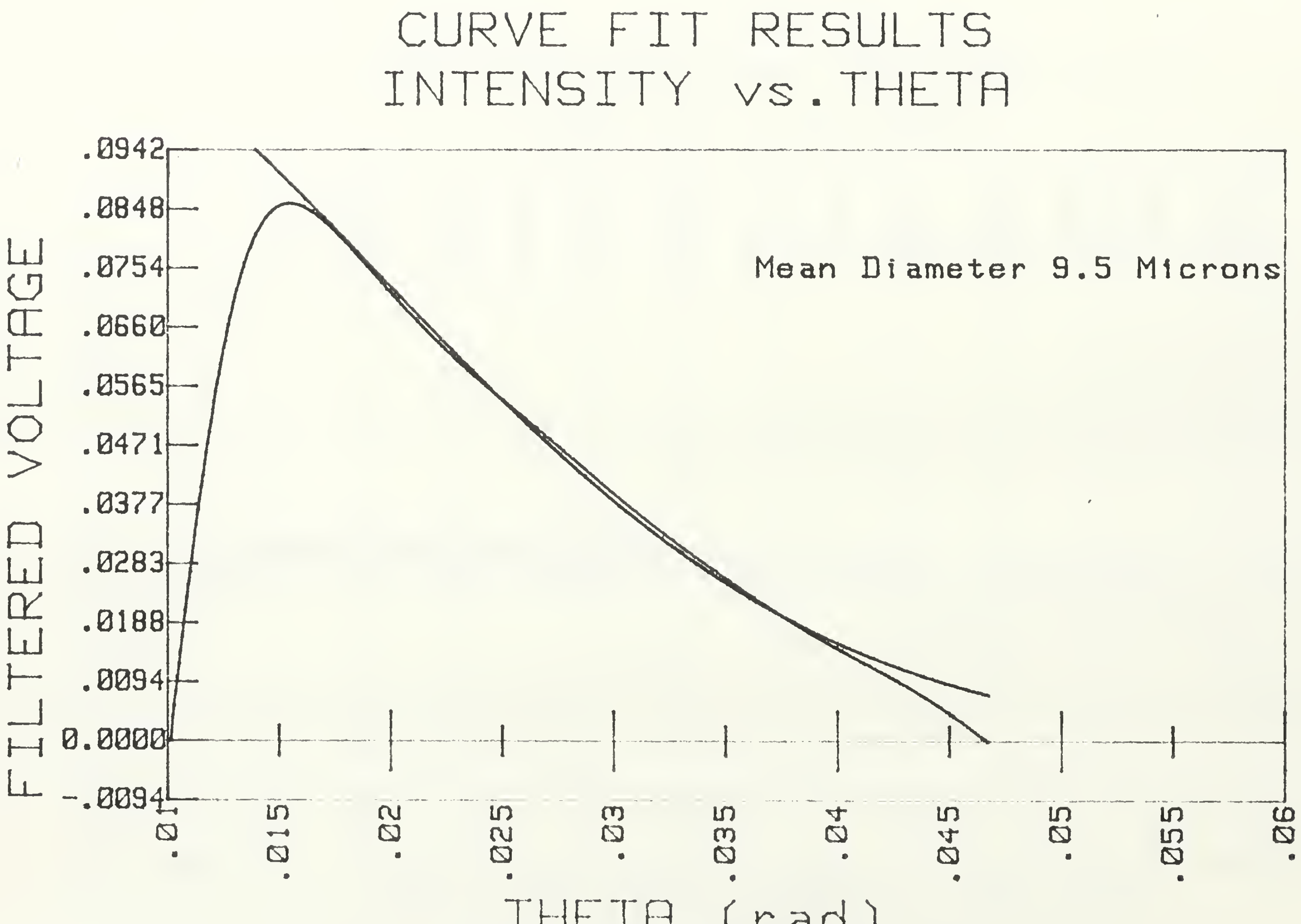


Figure 4.9 Curve Fit Method, 60% Transmitted Light

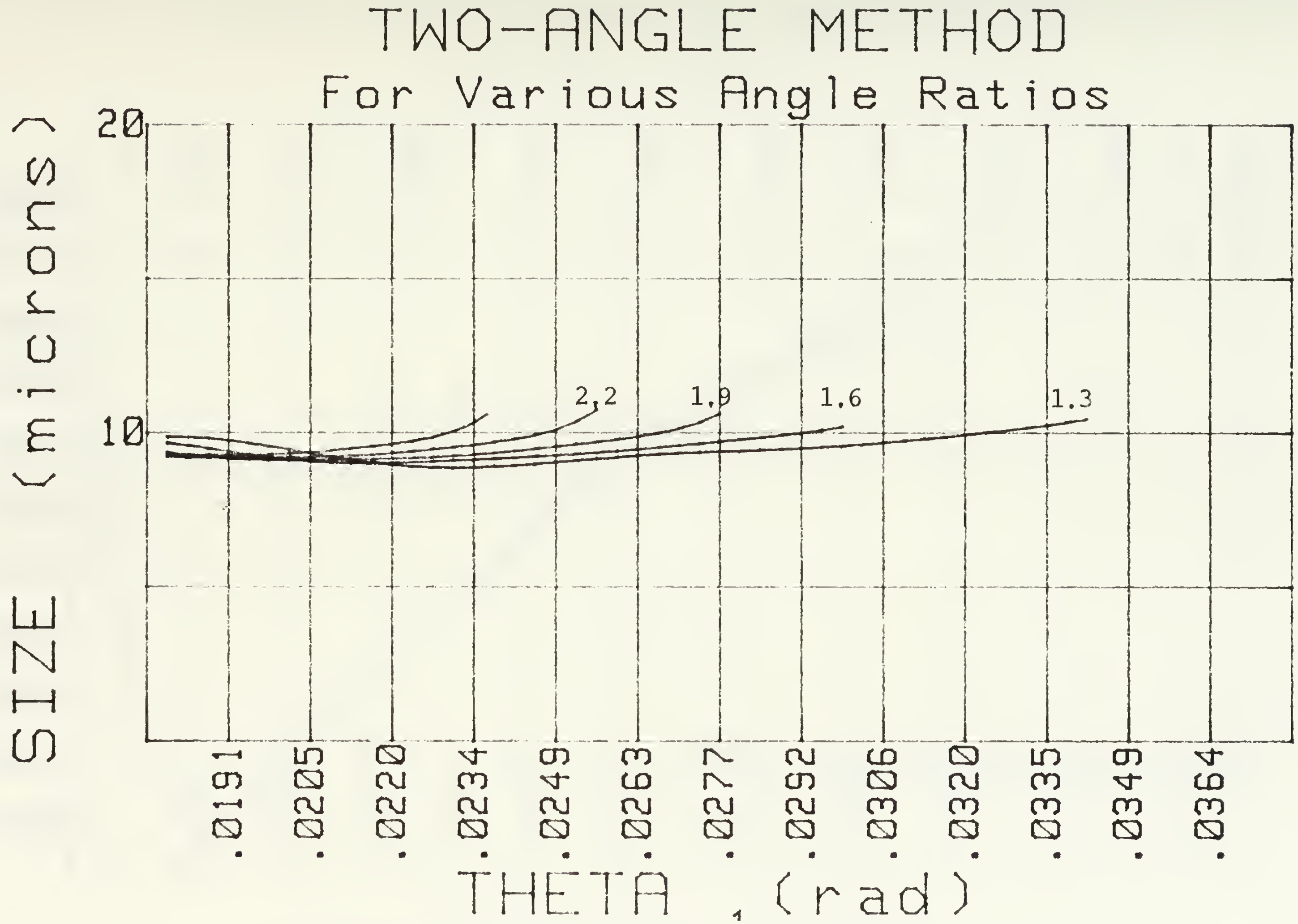


Figure 4.10 Two Angle Method, 60% Transmitted Light

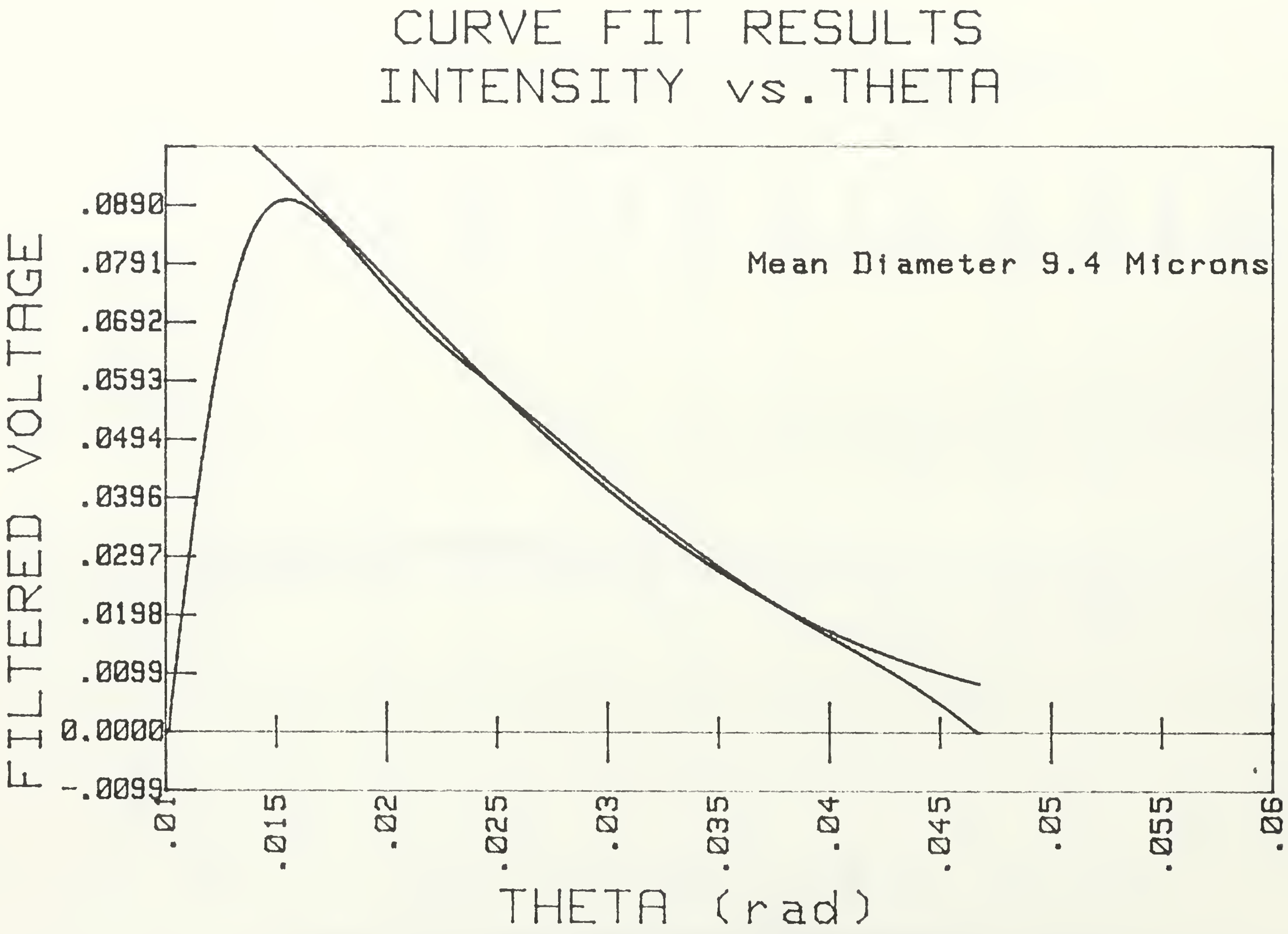


Figure 4.11 Curve Fit Method, 50% Transmitted Light

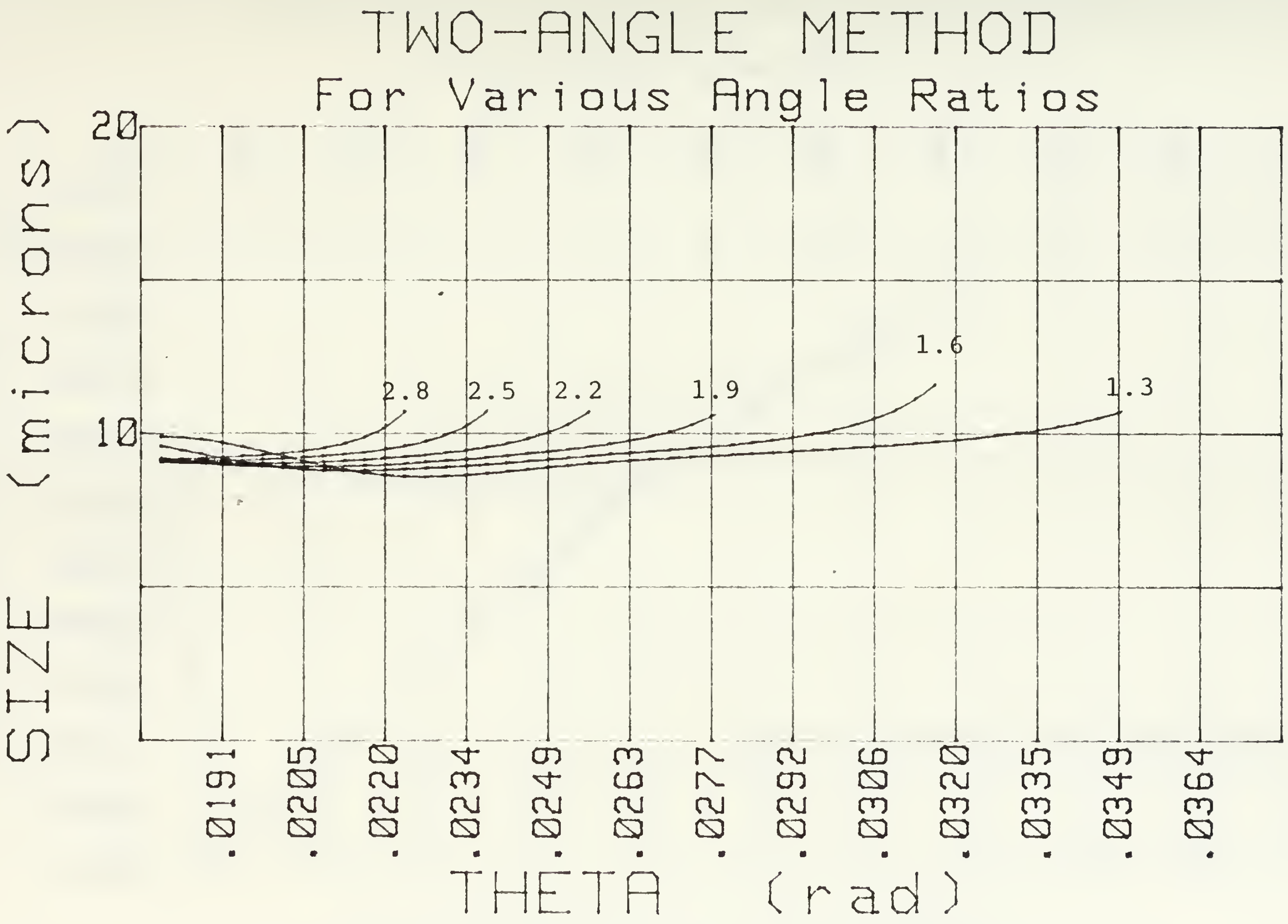


Figure 4.12 Two Angle Method, 50% Transmitted Light

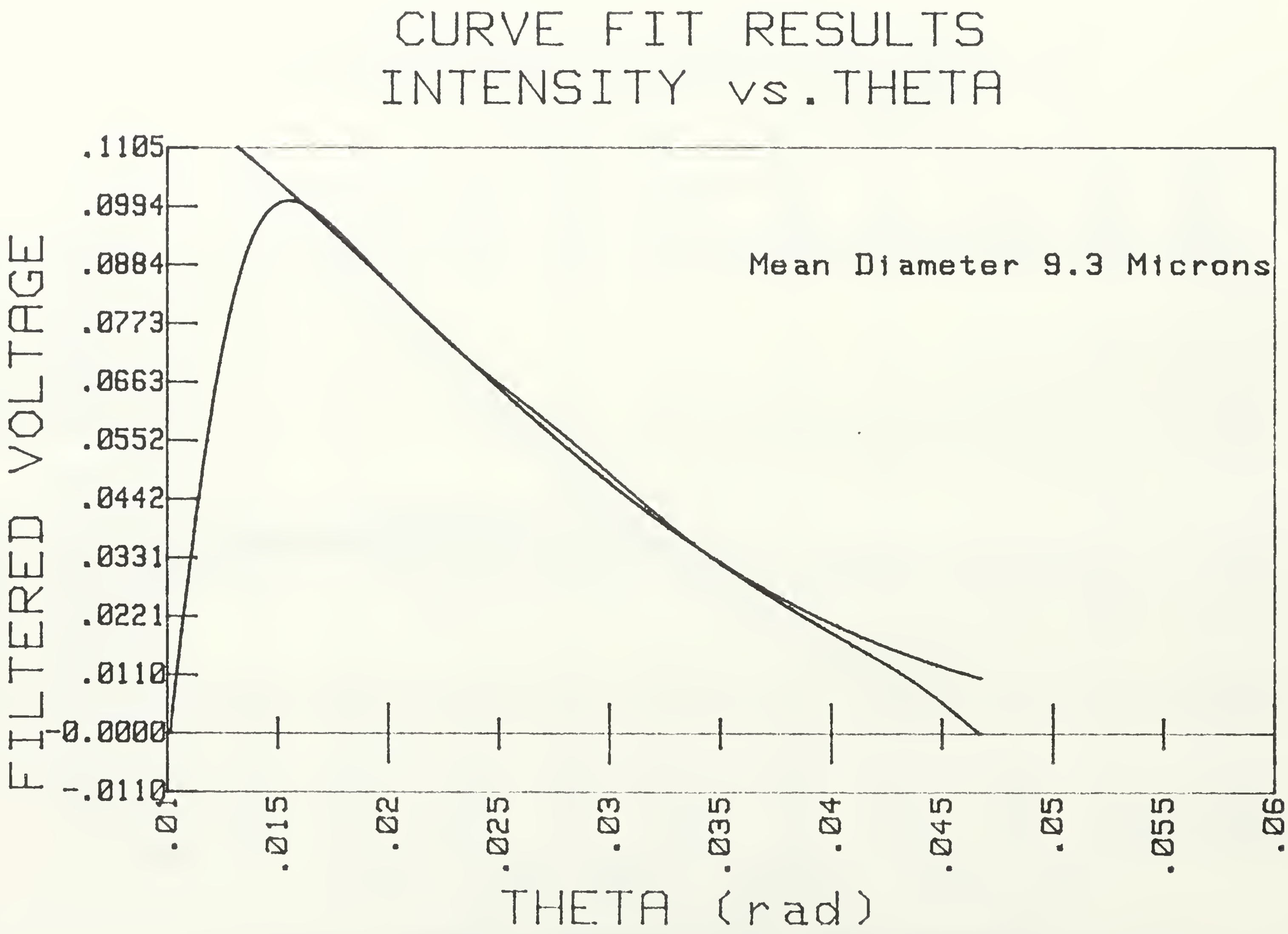


Figure 4.13 Curve Fit Method, 30% Transmitted Light

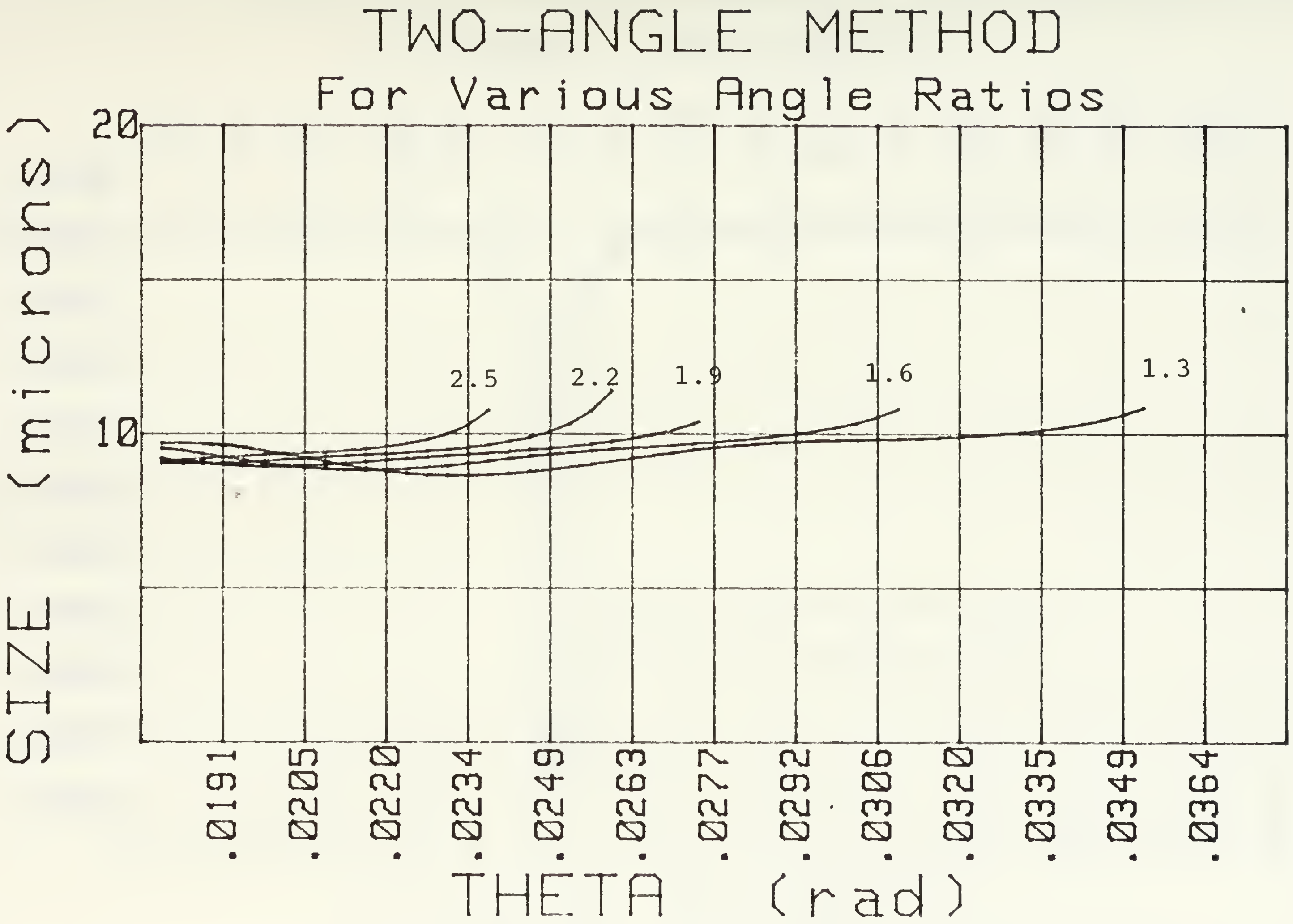


Figure 4.14 Two Angle Method, 30% Transmitted Light

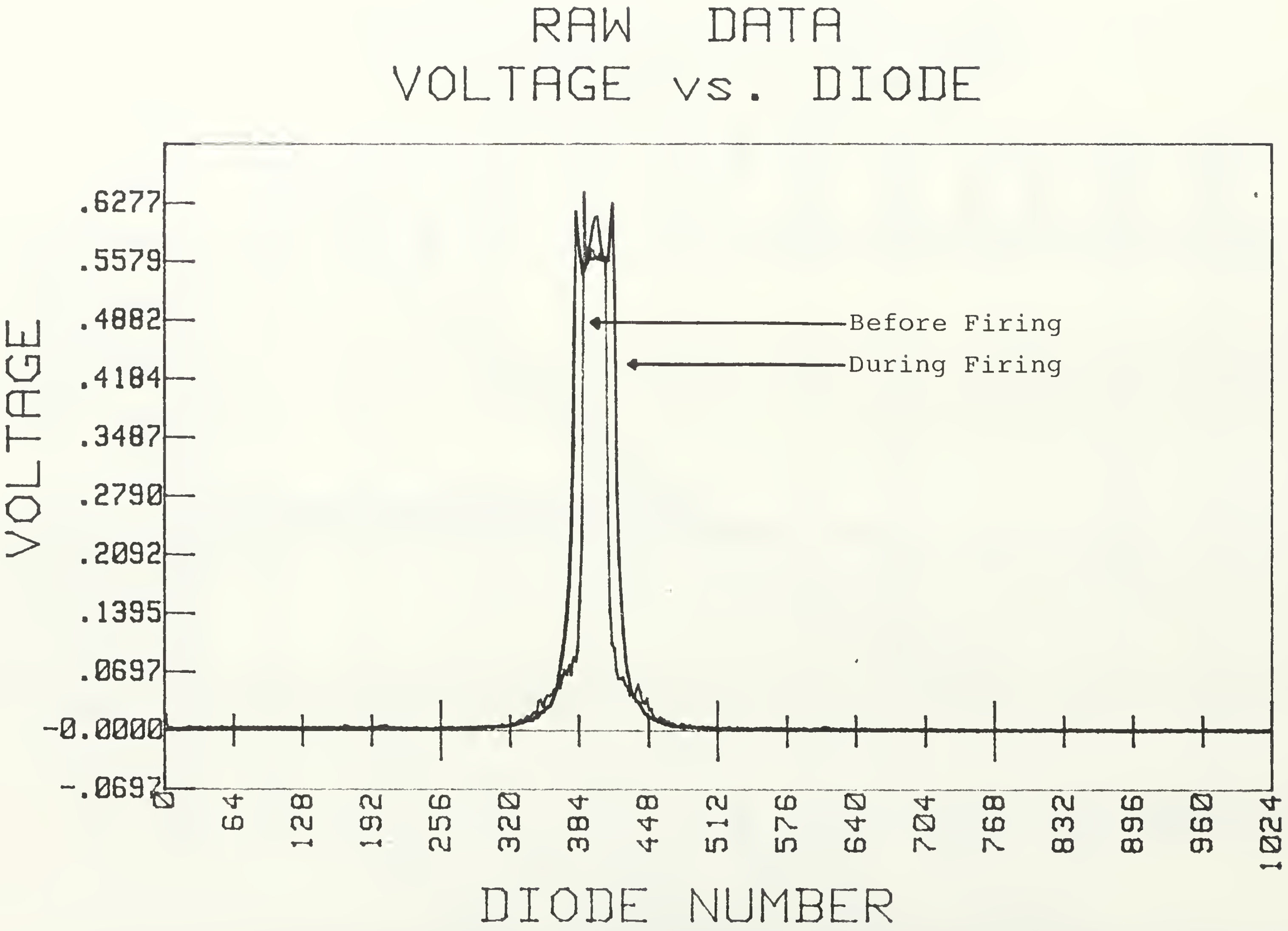


Figure 4.15 2% Aluminum Propellant, Less Than 90% Attenuation

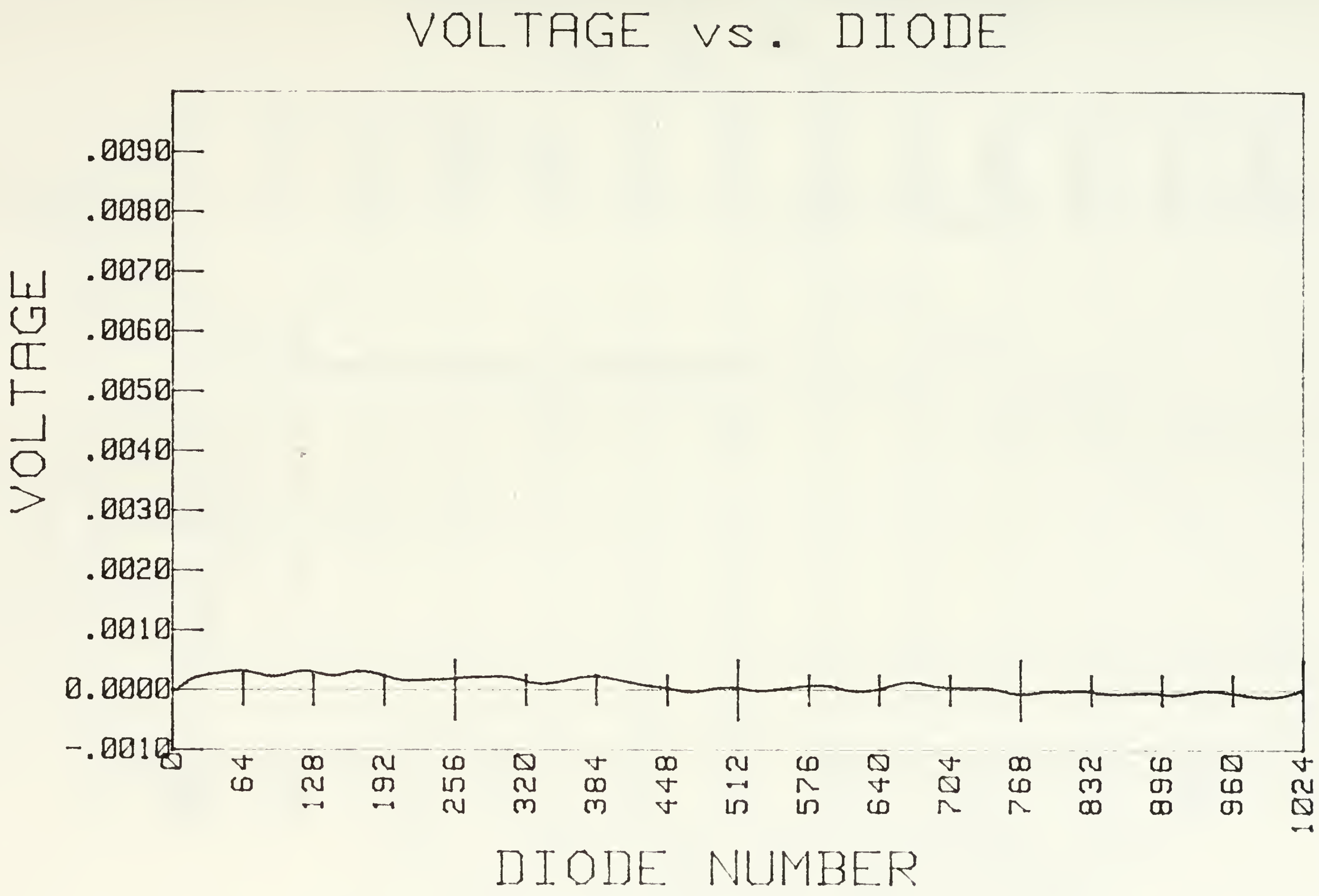


Figure 4.16 Non-Metalized Propellant, 22 Oct., Exhaust

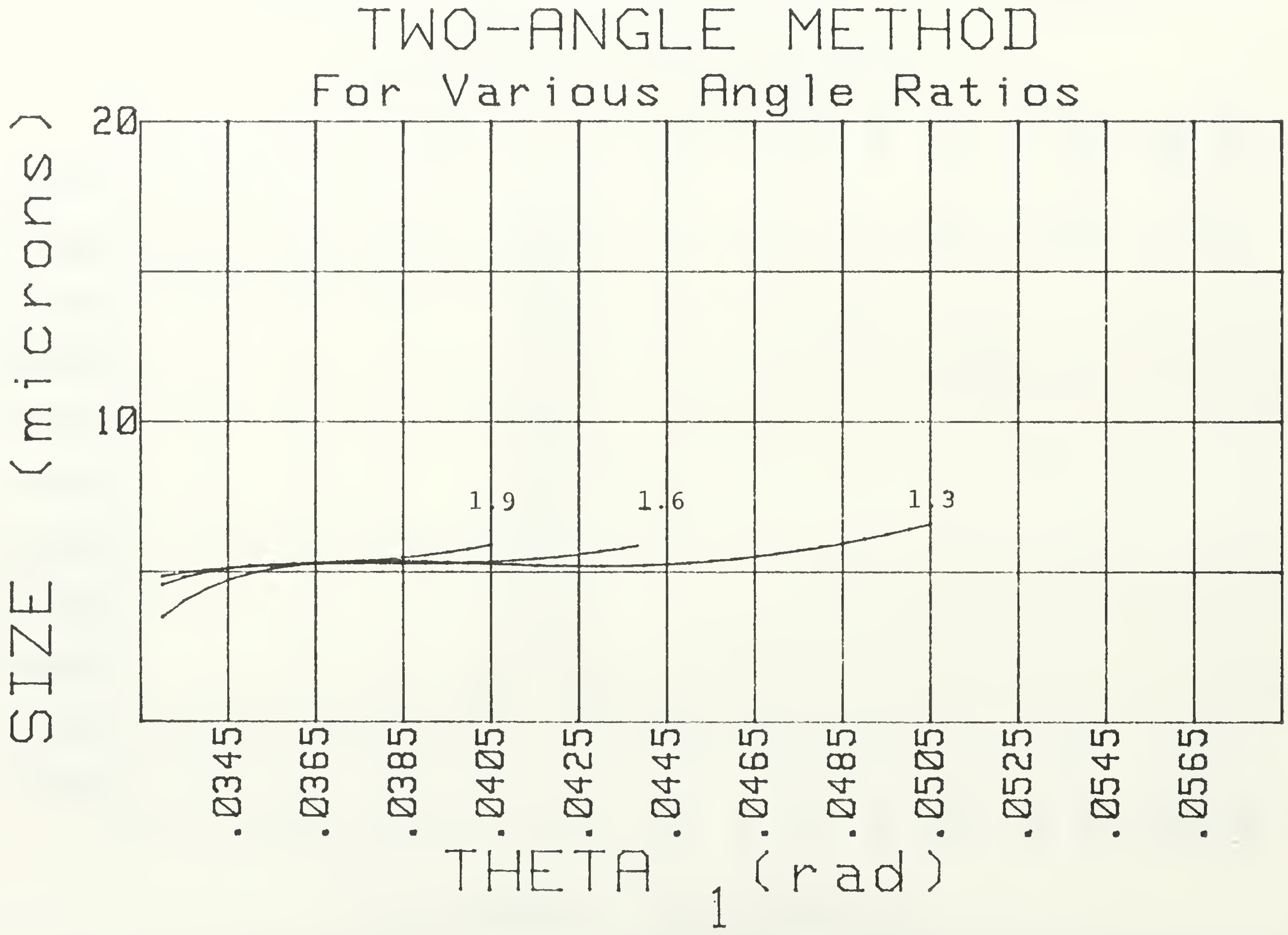


Figure 4.17 4.8% Aluminum Propellant, 18 Oct., Exhaust

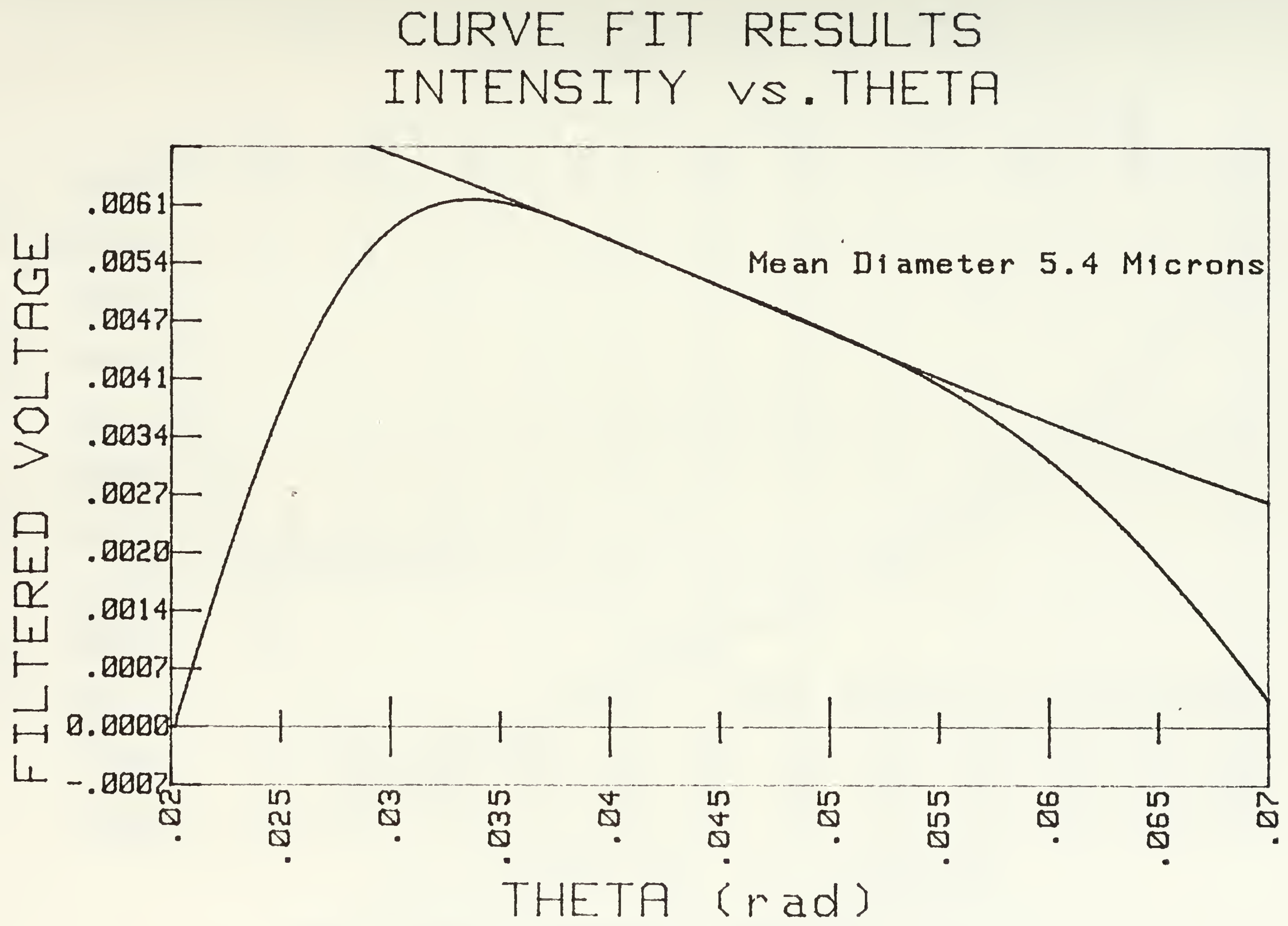


Figure 4.18 4.8% Aluminum Propellant, 18 Oct., Exhaust

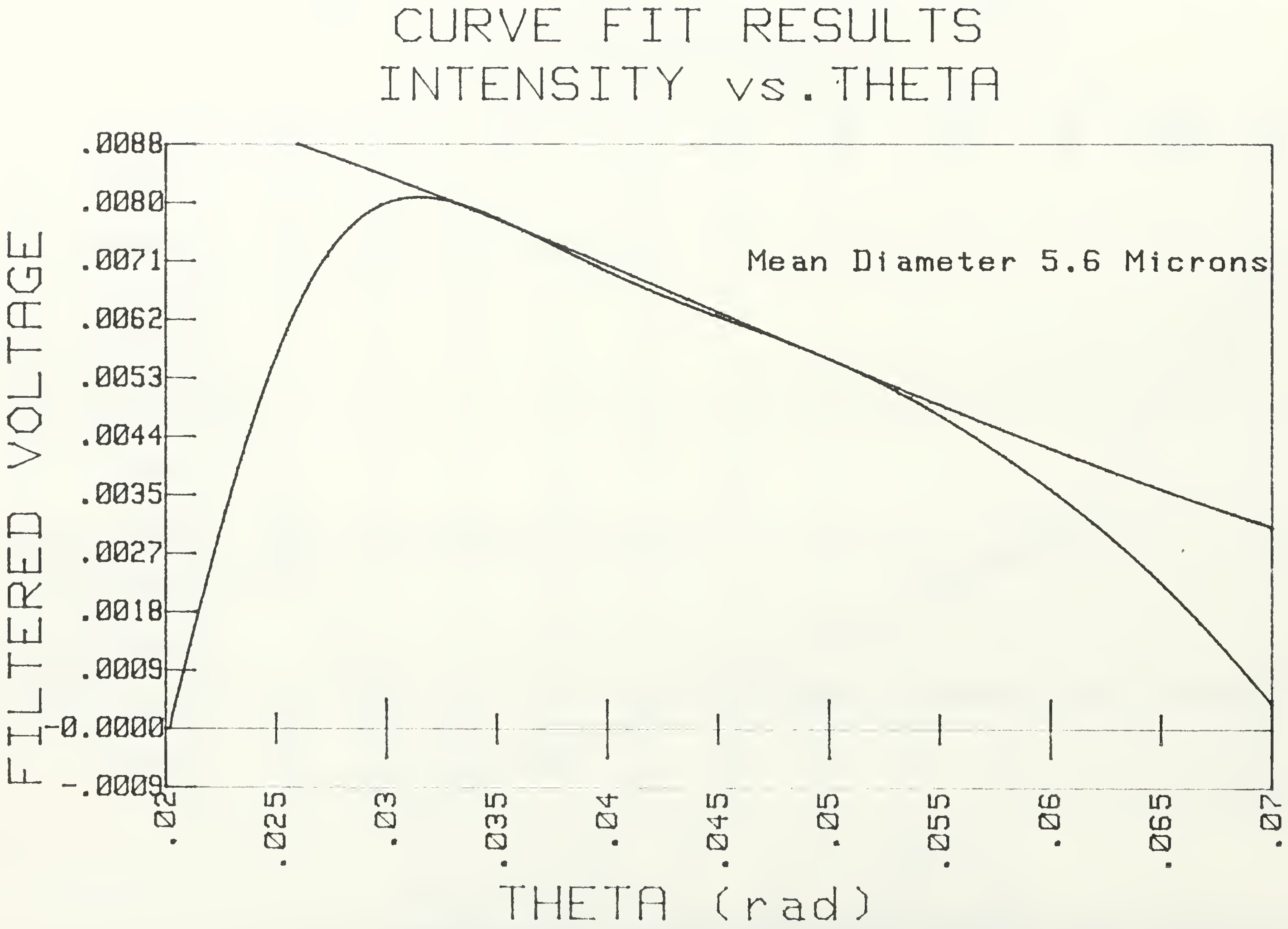


Figure 4.19 4.8% Aluminum Propellant, 23 Oct., Exhaust

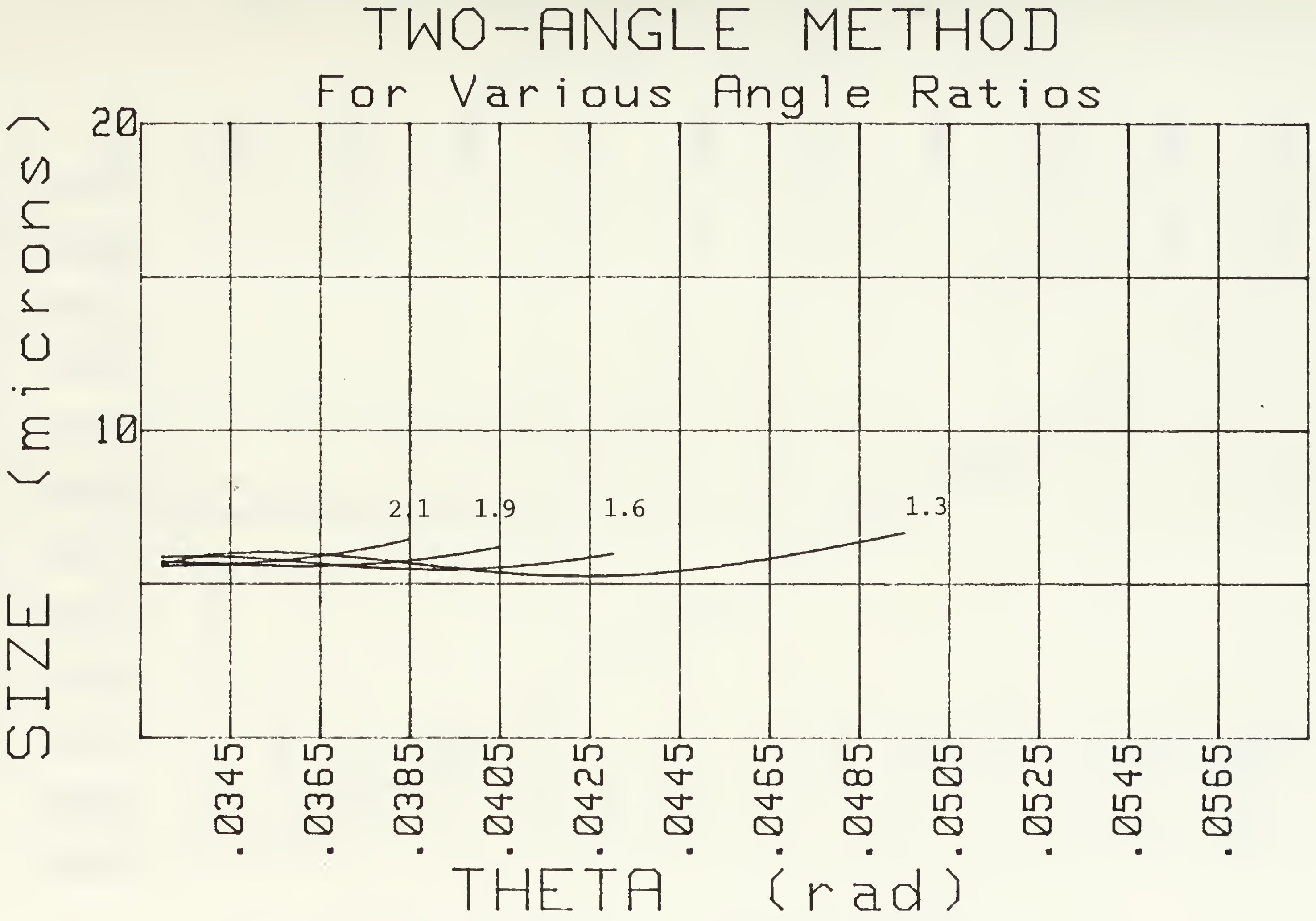


Figure 4.20 4.8% Aluminum Propellant, 23 Oct., Exhaust

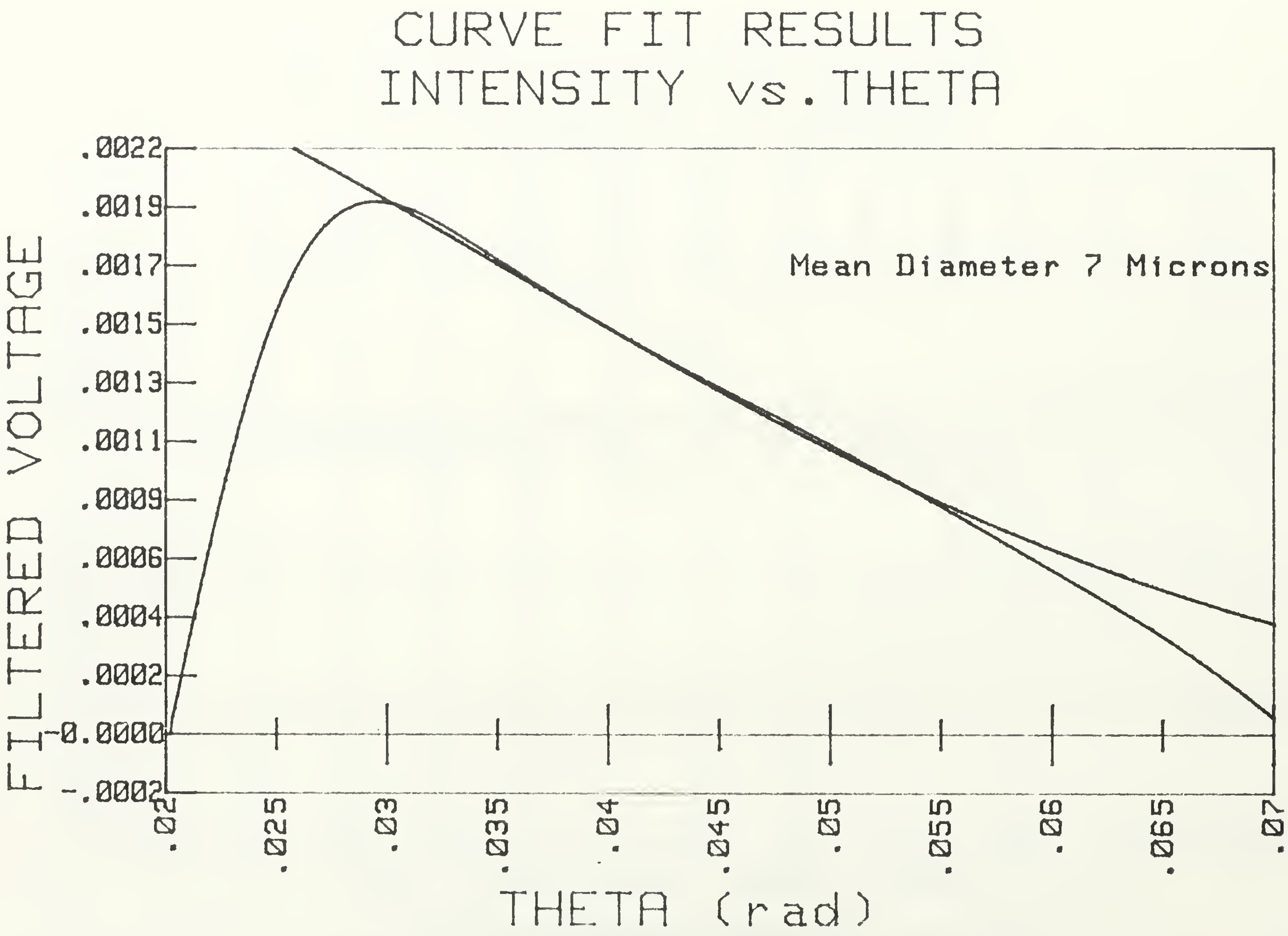


Figure 4.21 2% Aluminum Propellant, 30 Oct., Exhaust

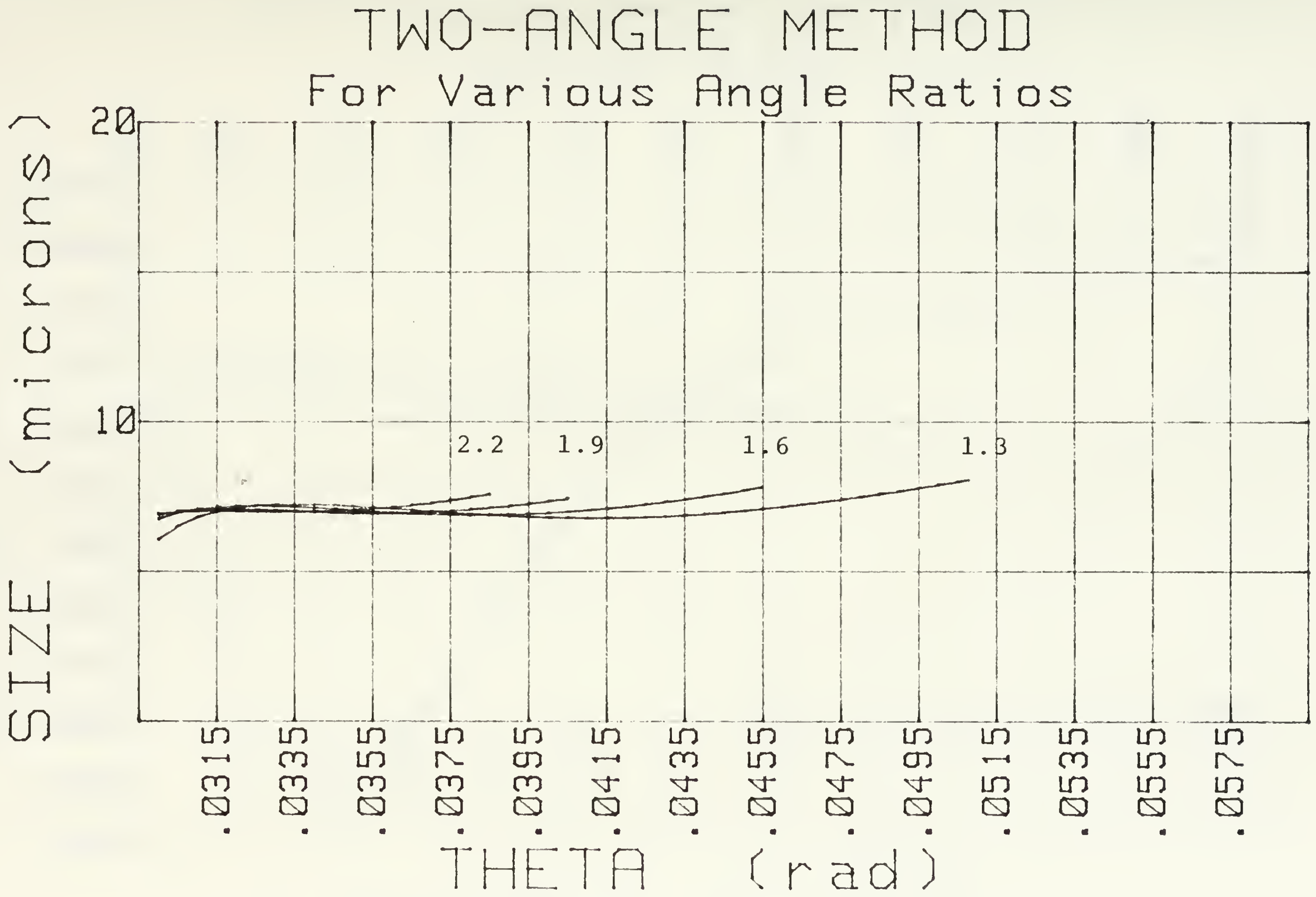


Figure 4.22 2% Aluminum Propellant, 30 Oct., Exhaust

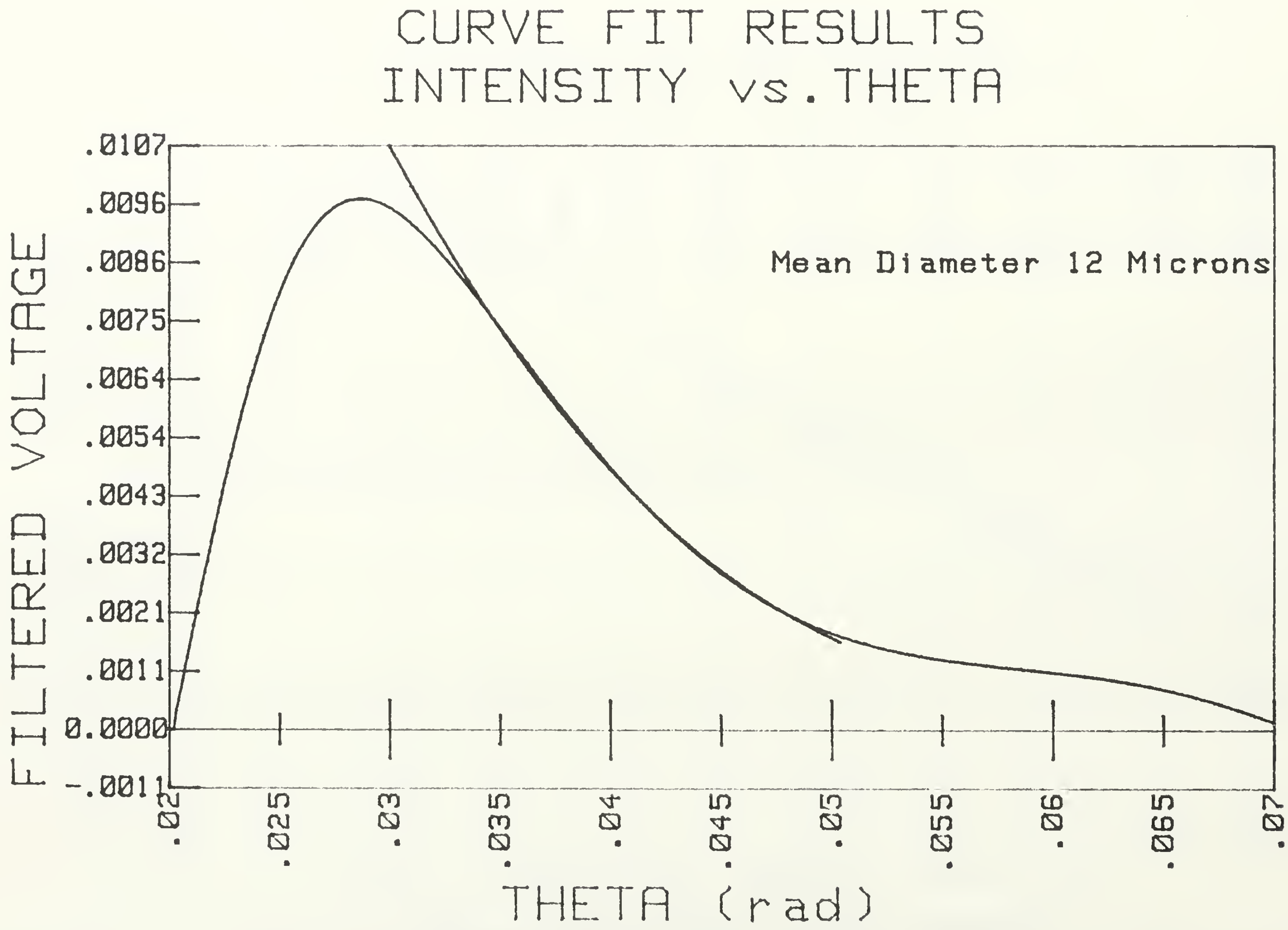


Figure 4.23 4.8% Aluminum Propellant, 19 Nov., Exhaust

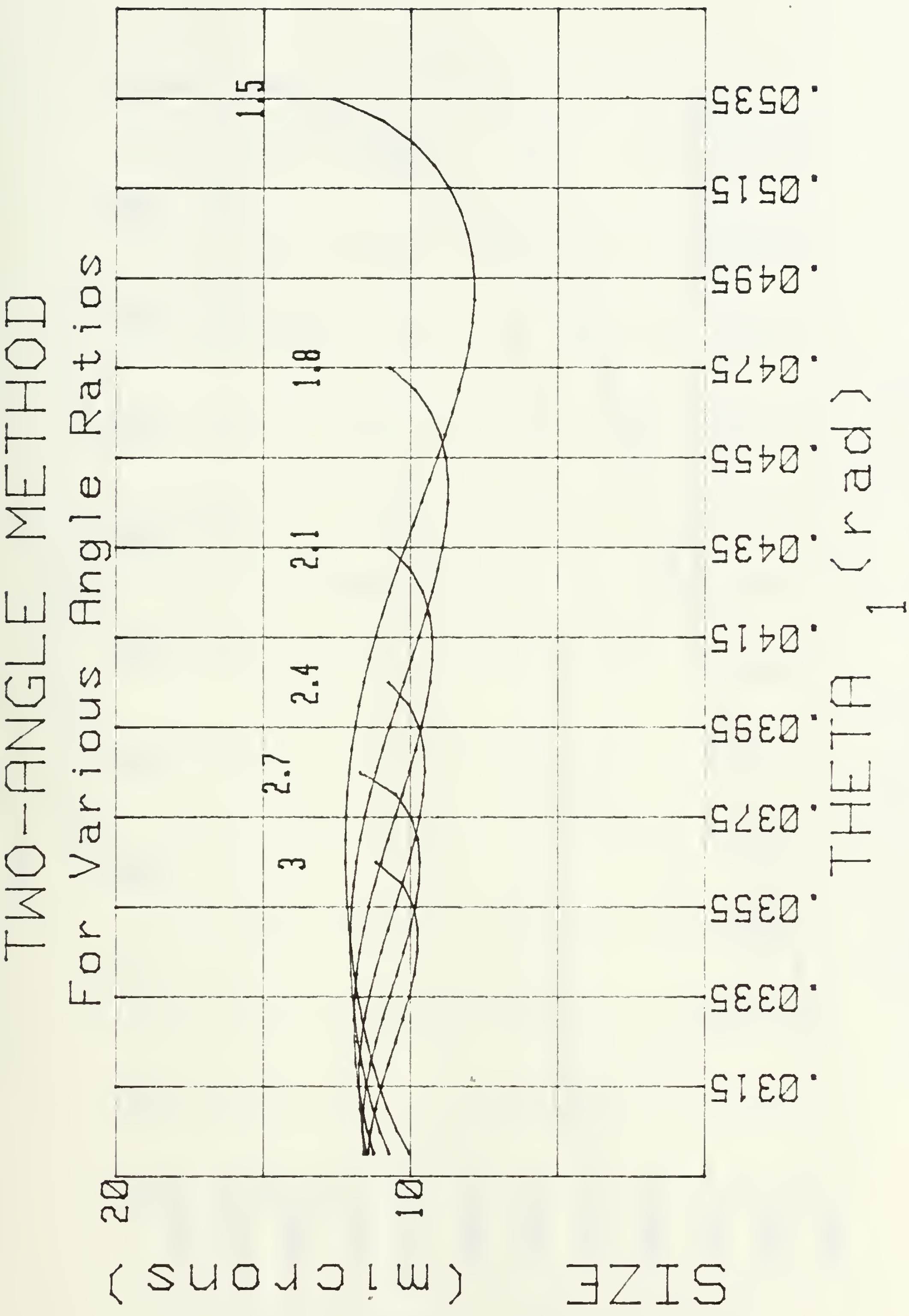


Figure 4.24 4.8% Aluminum Propellant, 19 Nov., Exhaust

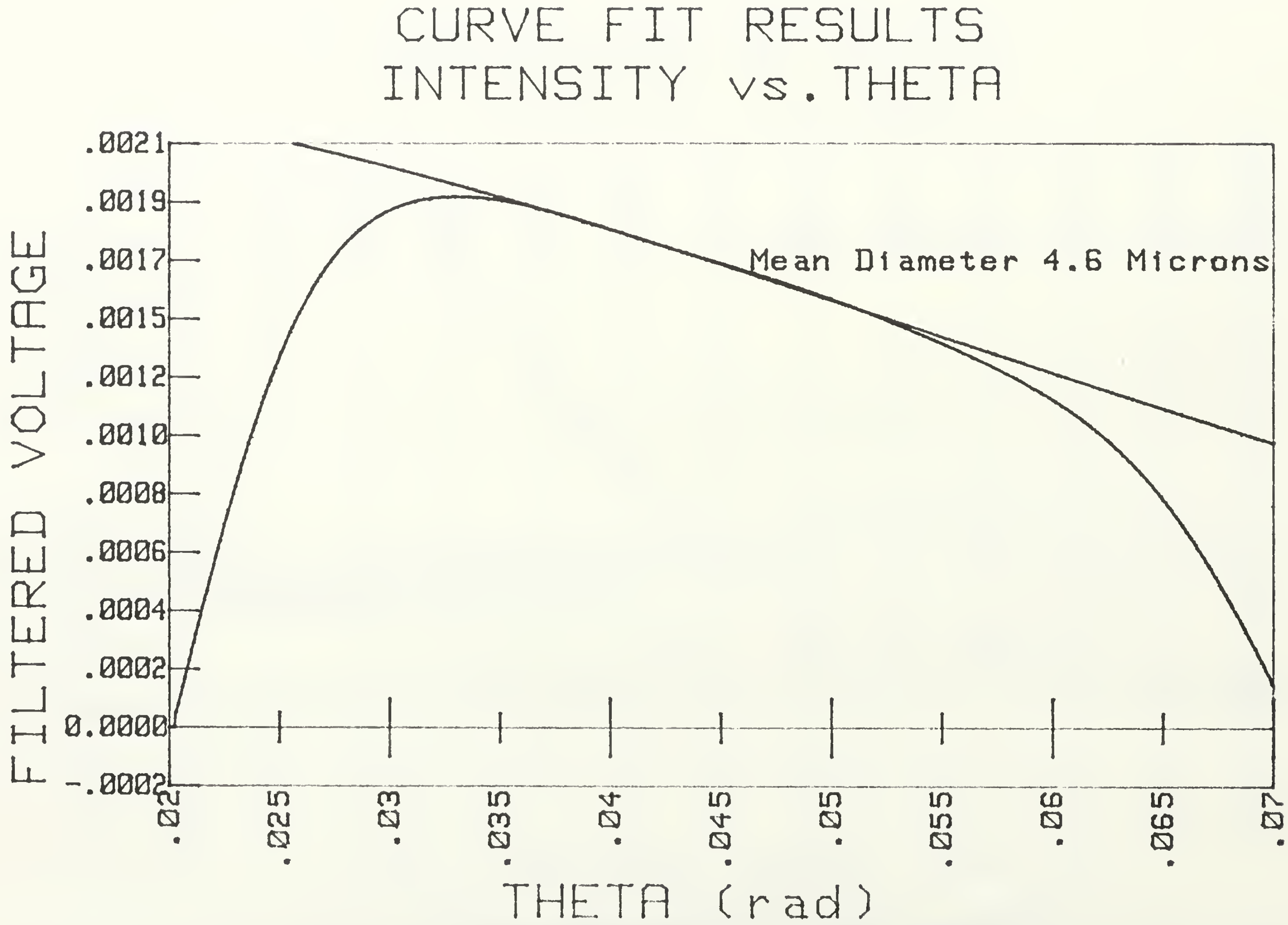


Figure 4.25 2% Aluminum Propellant, 25 Nov., Exhaust

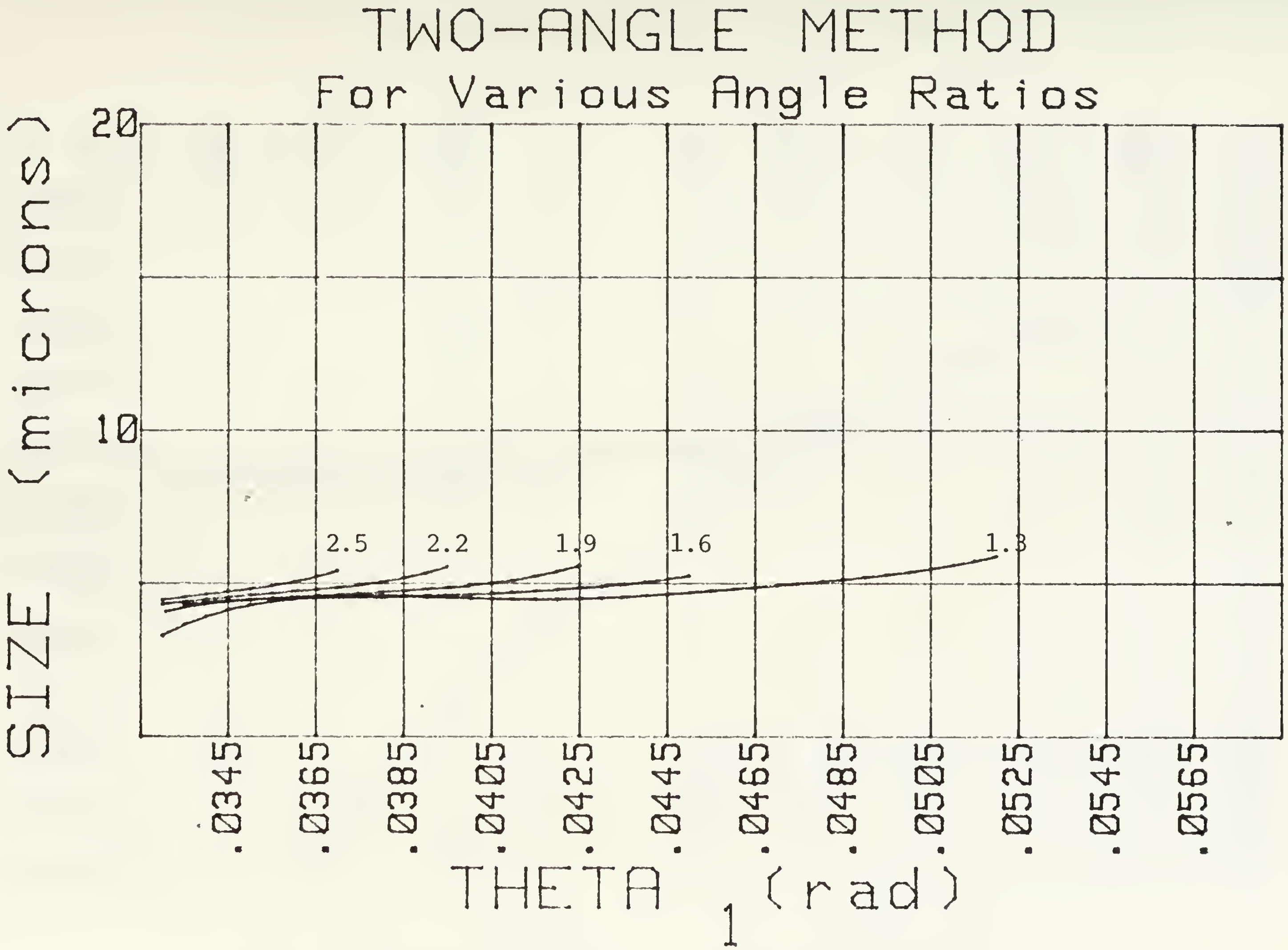


Figure 4.26 2% Aluminum Propellant, 25 Nov., Exhaust

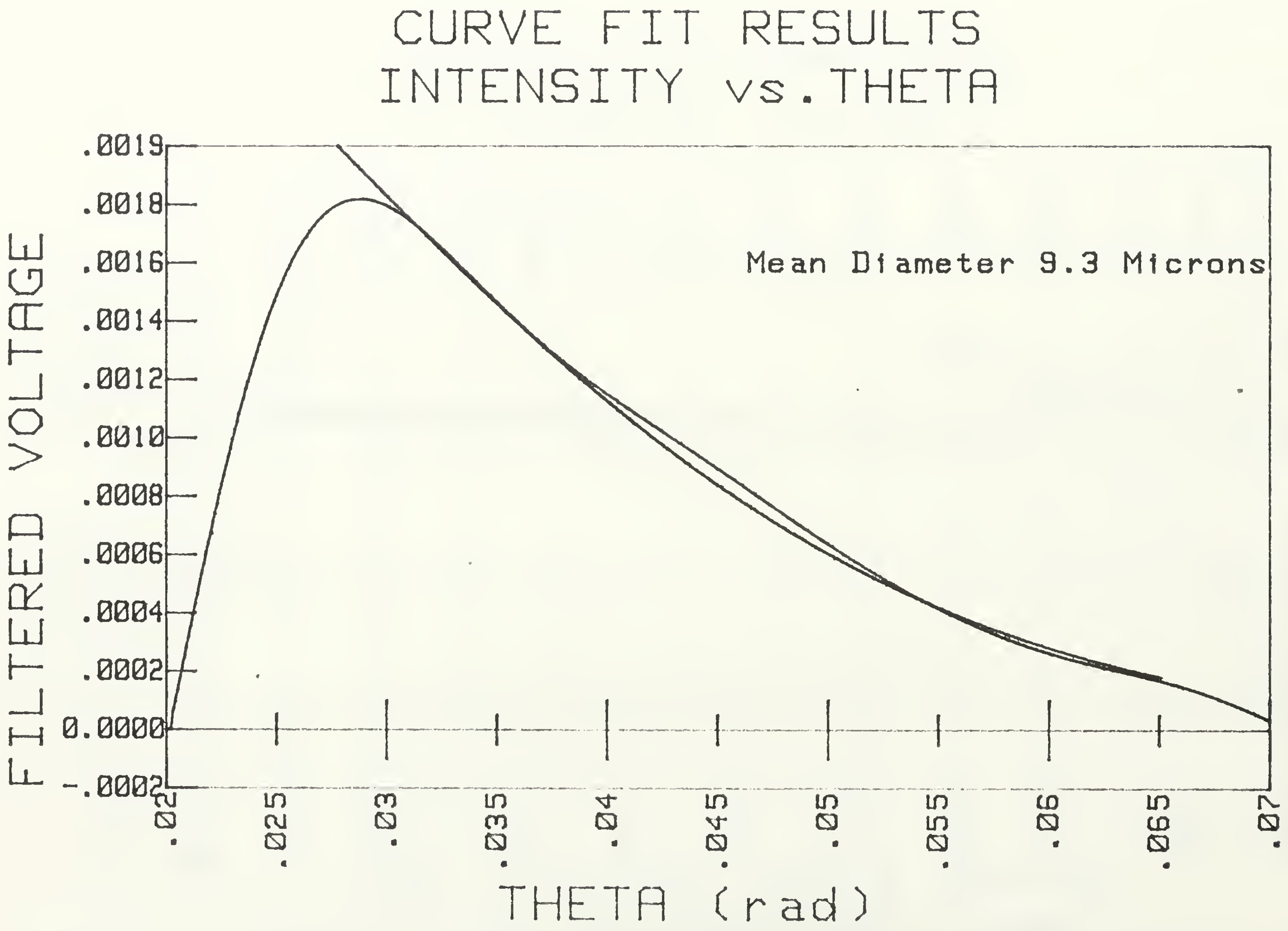


Figure 4.27 2% Aluminum Propellant, 26 Nov., Exhaust

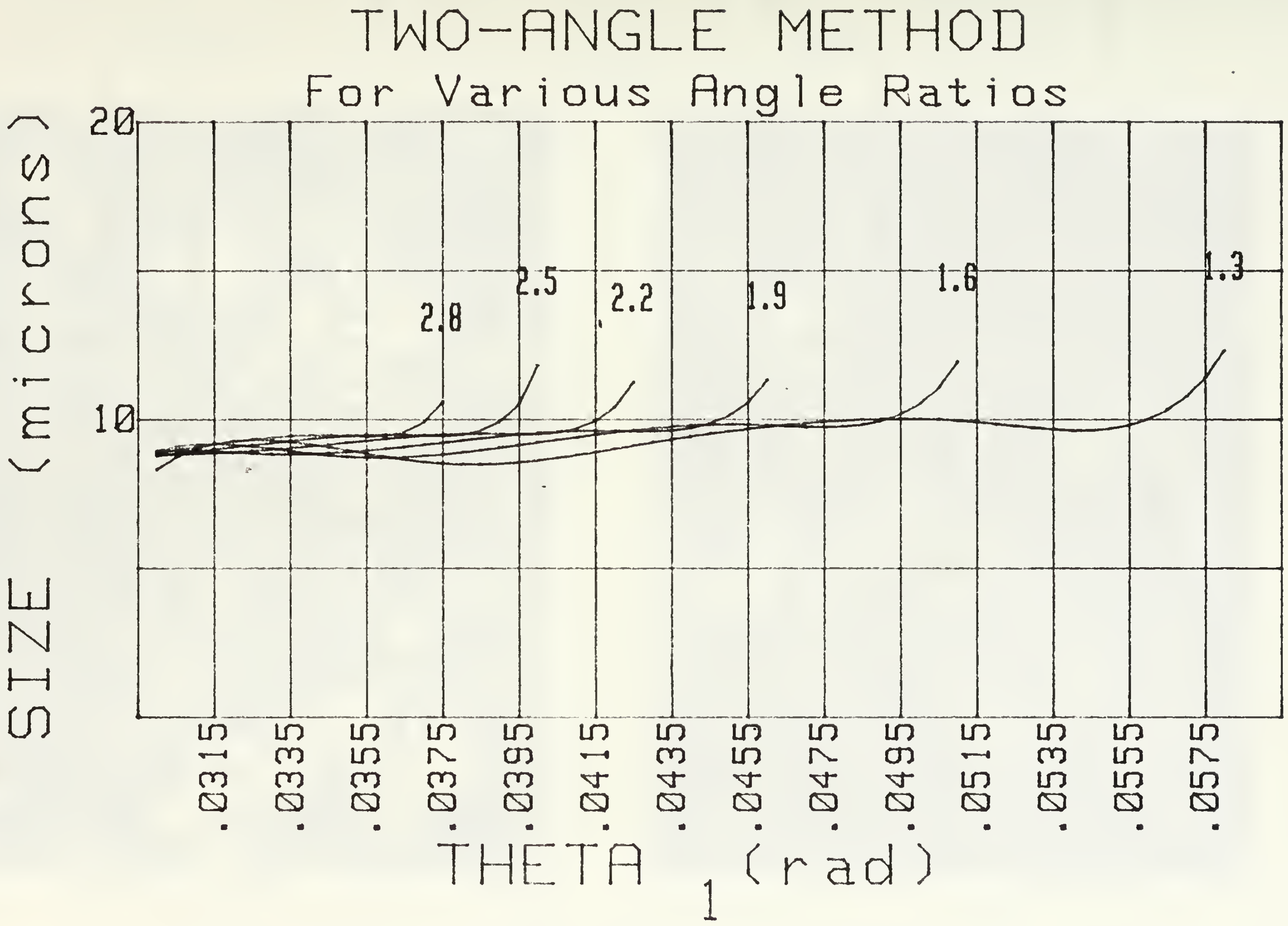
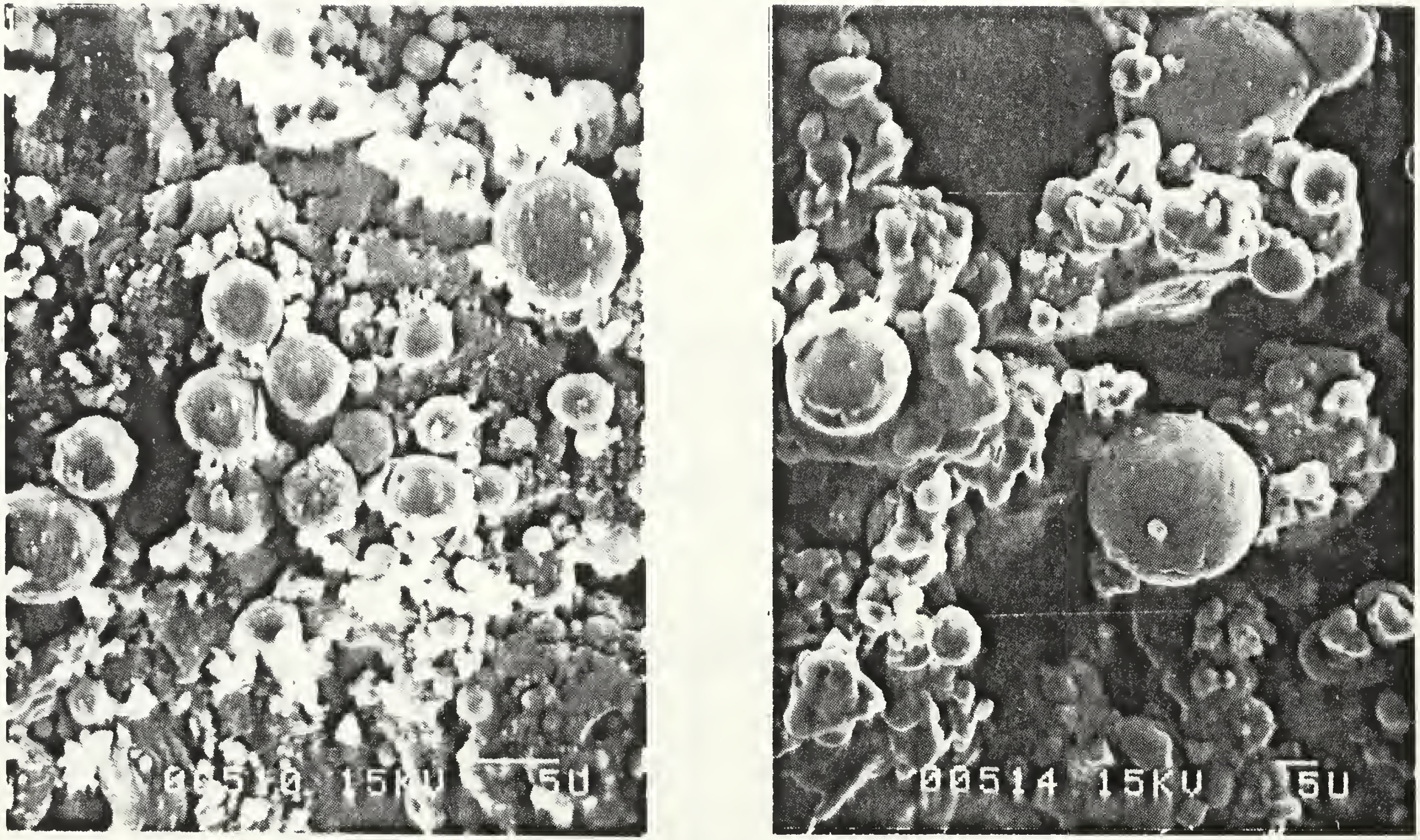


Figure 4.28 2% Aluminum Propellant, 26 Nov., Exhaust



Exhaust

Motor

Figure 4.29 SEM Eval., 2% Al Propellant

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this study have shown that the measurement of D_{32} in rocket motor exhausts can be made using quite simple light scattering methods. Apparatus calibration results and S.E.M. evaluations of the collected motor exhaust products support this conclusion.

The SPP equation model underestimated D_{43} for this investigation. This indicated that the model predictions cannot be extrapolated to small motors with throat diameters less than one inch. The light scattering method, however, can be used to validate the SPP model for the larger motors upon which it was based.

In order to improve the signal to noise ratio in regards to the scattered light intensity, it is recommended that the laser beam be moved closer to the exit plane of the nozzle, where the particle density is greater. The laser beam for this study was 7.3 centimeters aft of the nozzle exit. To resolve the combustion light problem it may be necessary to use a different laser, such as a CO_2 that has a different wavelength than present in the combustion process. Also, other binder systems should be tested to determine if they significantly alter the light spectrum.

APPENDIX

PROGRAM LISTINGS

```
10    !********************************************************************
20    !*******************             RDC             ********************
30    !*******************        PLOTS RAW DATA       ********************
40    !*******************          AVERAGES           ********************
50    !*******************           FILTERS           ********************
60    !*******************  DETERMINES MEAN DIAMETER   ********************
70    !*******************  BY INTERACTIVE GRAPHICS    ********************
80    !*******************  AND THE TWO-ANGLE METHOD   ********************
90    !*******************     Robert Kelly Harris  84 ********************
100   !*******************     Revised, John S Rosa 85 ********************
110   !********************************************************************
120   OPTION BASE 1
130   COM /Hrdgaus/ Av2(1024)
131   COM A2(1024) BUFFER
140   COM /Gauss/ T1(1024),L
150   COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx
160   COM /Readata/ B,P,H,Q3$[20],Q4$[20],Zz$[20],Y1(8192) BUFFER,Y2(8192) BUFFE
R
170   COM /Two/ Av1(1024),M,M1,F
180   DIM Scans(8),X(1024)
190   COM /Plots/ P1$[20],P2$[20],P3$[20],P4$[20]
200   INTEGER Graf(1:12480) BUFFER
210 Choose:  PRINT CHR$(12)
220   Old=0
230   PRINT " TO LOOK AT ANY DATA FILE THE PROGRAM NEEDS SOME STARTING INFORMATI
ON"
240   PRINT ""
250   PRINT "         TO ACCOUNT FOR THE CHANGE IN WAVELENGTH IN THE MEDIUM"
260   PRINT ""
270   PRINT "               ENTER THE INDEX OF REFRACTION OF THE MEDIUM"
280   PRINT ""
290   PRINT "                                 WATER = 1.33"
300   PRINT "                                   AIR = 1.0"
310   PRINT "                   ESTIMATE OF EXHAUST = 1.1"
320   BEEP
330   INPUT "         THIS VALUE ADJUSTS THE COMPARISON CURVE TO THE MEDIUM",M1
340   PRINT CHR$(12)
350   PRINT "    TO ACCOUNT FOR REFRACTION OF LIGHT AT BOUNDARIES BETWEEN"
360   PRINT ""
370   PRINT "  THE MEDIUM AND AIR YOU MUST ENTER THE INDEX OF REFRACTION   "
380   PRINT ""
```

```
390   PRINT "      OF THE COMBINATION OF THE MEDIUM AND ITS BOUNDARY"
400   PRINT ""
410   PRINT "            THIS VALUE IS APPLIED DIRECTLY TO THE DATA"
420   PRINT ""
430   PRINT "               AIR=1.0                PLEXIGLASS & WATER = 1.39"
440   PRINT ""
450   PRINT "ESTIMATE OF  MOTOR CAVITY COMBUSTION PRODUCTS & WINDOW = 1.22"
460   PRINT ""
470   PRINT "                     ESTIMATE OF ROCKET EXHAUST  = 1.1 OR 1.0"
480   INPUT M
490   PRINT CHR$(12)
500   INPUT "                 ENTER LASER WAVELENGTH (HeNe=.6328,Ar=.488)",L
510   INPUT "ENTER THE DESIRED PLOTTING INTERVAL OF DIODE ARRAY (2,4,6)",H
520   F=500                                 !mm  FOCUL LENGTH OF OBJECTIVE LENS
521   X(1)=1
522   T1(1)=.02
530   Diod=.025                             !mm  DIODE SPACING MAY BE .03
540        FOR I=1 TO 1023
550        X(I+1)=I+1                        !CREATE AN ARRAY OF DIODE NUMBERS
560        T1(I+1)=ATN((I*Diod)/(F*M))+T1(1)       !CREATE AN ARRAY OF THETA
570        NEXT I
580   PRINT CHR$(12)
590   CALL Displav1(Old)                    !JUST PRINTS INITIAL REMARKS ON CRT
600   IF Old THEN CALL Review(Av1(*))       !THESE TWO LINES ALLOW FOR
610   IF Old THEN GOTO Gauss                !REVIEWING REDUCED DATA FILES
620   BEEP
630   INPUT "              INPUT TWO FILENAMES NOW (NO-PART ,PART)",Q3$,Q4$
640   INPUT "          ENTER '1' FOR 8 SCANS    '2' FOR 4 SCANS",P
650   Zz$=":INTERNAL,4,1"               ! USES LEFT DISK DRIVE FOR RAW DATA FILES
660   CALL Readata
670   CALL Shift
680   BEEP
690 Screen:  !
700   PRINT CHR$(12)                         !CLEARS SCREEN
710   P1$="VOLTAGE"
720   P2$="DIODE NUMBER"                     ! STRINGS FOR PLOTS
730   P3$="VOLTAGE vs. DIODE"
740   P4$="RAW  DATA"
750   M5=1024
751   M8=0.
760   Xt=64                                  ! SET UP VALUES FOR PLOTS
770   Yt=.04
780   Xm=4
790   Ym=5
791   Xx=0
800   CALL Plot(Y2(*))                       ! DRAWS AXES ,ETC...
810   GSTORE Graf(*)                         ! STORES GRAPHICS DISLAY JUST MADE
820   CALL Dataplot(B,Y1(*),H)               !PLOT NO-PARTICLES DATA
830   PRINT "                                   NO-PARTICLES PLOTTED"
840   PRINT ""
850   PRINT "                                 HOW MANY SCANS SEEM TO BE GOOD ?"
860   INPUT J
```

```
870   PRINT ""
880   PRINT "             WHICH SCANS ARE GOOD ?...ie...1,2,4,5,7,INCLUDE LAST CO
MMA"                      !LAST COMMA IS REQUIRED OR YOU HAVE TO HIT CONT.. TWICE
890   INPUT Scans(*)
900   PRINT CHR$(12)
910   PRINT USING "//////////"
920   PRINT "                             AVERAGING THE SELECTED SCANS"
930   GRAPHICS OFF
940   CALL Average(J,Scans(*),Y1(*),Av1(*))
950   PRINT USING "@"
960   GLOAD Graf(*)       !LOADS GRAPHICS ARRAY RATHER THAN WASTE TIME RE-DRAWING
970   GRAPHICS ON
980   CALL Result(Av1(*),X(*),H)                       ! PLOTS 1024 ELEMENT ARRAYS
990   PRINT USING "//"
1000  PRINT "                             Average Intensity No-Particles"
1010  ON KEY 0 LABEL "AVERAGE1" GOTO Screen
1020  ON KEY 1 LABEL "PLOT-PARTICLES" GOTO 1060
1030  PRINT "                     PRESS KEY # 0 TO RE-AVERAGE OR # 1 TO CONTINUE"
1040 Standby:                   ! MANUAL CALLS THIS INTERRUPT DRIVEN PROGRAMMING
1050       GOTO Standby                     ! LOOPS, WAITING FOR USER TO DECIDE
1060  PRINT USING "@"
1070  OFF KEY 1                      !HELPS AVOID CONFUSION BY CLEARING THAT BOX
1080  CALL Dataplot(B,Y2(*),H)                              !PLOT PARTICLES DATA
1090  PRINT USING "/"
1100  PRINT "                                             PARTICLE DATA PLOTTED"
1110  PRINT "          FOR A HARD COPY OF THIS RAW DATA PRESS KEY # 6"
1120  PRINT " "
1130  PRINT "                         OR     TO CONTINUE PRESS KEY # 1"
1140  ON KEY 6 LABEL "HARD & RAW" GOTO Raw
1150  ON KEY 1 LABEL "CONTINUE " GOTO Select
1160  GOTO Standby
1170 Raw:  CALL Plot(Y2(*),1)           ! THE ONE (1) IS AN OPTIONAL PARAMETER
1180       CALL Dataplot(B,Y2(*),H)     ! WHICH IS USED TO GET HARD COPIES
1190 Select:!
1200       OFF KEY 6
1210       OFF KEY 1
1220  PRINT CHR$(12)
1230  PRINT USING "////"
1240  PRINT "                                   HOW MANY SCANS SEEM TO BE GOOD ?"
1250  INPUT J
1260  PRINT "                     WHICH SCANS ARE GOOD ?...ie...1,2,4,5,7,INCLUDE
 LAST COMMA"
1270  INPUT Scans(*)
1280  PRINT CHR$(12)
1290  PRINT USING "//////////"
1300  GRAPHICS OFF
1310  PRINT "                             AVERAGING THE SELECTED SCANS"
1320  CALL Average(J,Scans(*),Y2(*),Av2(*))
1330  PRINT USING "@"
1340  P4$="AVERAGED SCANS"
```

```
1350  CALL Plot(Av2(*))
1360  GRAPHICS ON
1370  GSTORE Graf(*)
1380  CALL Result(Av2(*),X(*),H)
1390  PRINT USING "//"
1400  PRINT "                                       Average Scattered Intensity"
1410  ON KEY 2 LABEL "AVERAGE2" GOTO 1080
1420  ON KEY 3 LABEL "SUBTRACT" GOTO 1450
1430  PRINT "                            HIT KEY # 2 TO RE-AVERAGE OR KEY # 3 TO
 CONTINUE"
1440  GOTO Standby
1450  PRINT USING "@"
1460  OFF KEY 3
1470  MAT Av1= Av2-Av1                     !SUBTRACTS NO-PARTICLES FROM PARTICLES
1480  GLOAD Graf(*)
1490  CALL Result(Av1(*),X(*),H)
1500  PRINT USING "///"
1510  PRINT "                     Plot of the Difference Between Particles and N
o-Particles"
1520  PRINT "                                              KEY # 6 FOR HARD COPY"
1530  PRINT "                                              KEY # 1  TO CONTINUE  "
1540  ON KEY 6 LABEL "  HARD AVERAGE" GOTO 1570
1550  ON KEY 1 LABEL "    FILTER   " GOTO 1600
1560  GOTO Standby
1570  CALL Plot(Av1(*),1)
1580  CALL Result(Av1(*),X(*),H)
1590  PLOTTER IS 3,"INTERNAL"
1600  PRINT USING "//"
1610  PRINT "                       ENTER THE NUMBER OF TIMES YOU WISH TO APPLY"
1620  PRINT "                            THE DIGITAL FILTER FOR SMOOTHING"
1630  PRINT "                                  EXAMPLE******** 10"
1640  PRINT "                                 TAKES ABOUT 1.5 MINUTES"
1650  INPUT "                                 ZERO IS ALSO ACCEPTABLE",Fil
1660  IF Fil=0 THEN Gauss
1670  P4$="FILTERED DATA"
1680  CALL Filter(Av1(*),Fil)
1690  PRINT CHR$(12)
1700  CALL Plot(Av1(*))
1710  IF Old THEN MAT X= T1
1720  CALL Result(Av1(*),X(*),H)
1730  PRINT "                     Plot of the Difference Between Particles and N
o-Particles"
1740  PRINT "                                  AFTER APPLICATION OF A DIGITAL FIL
TER"
1750  PRINT "                                             for a HARD COPY  "
1760  PRINT "                                           PREPARE the PLOTTER and"
1770  PRINT "                                               PRESS KEY # 8"
1780  PRINT "                                                   OR"
1790  PRINT "                                        PRESS KEY # 9 TO NORMALIZE"
1800  ON KEY 8 LABEL "HARD FILTERED" GOTO 1830
1810  ON KEY 9 LABEL "  NORMALIZE  " GOTO Gauss
```

```
1820  GOTO Standby
1830  CALL Plot(Av1(*),1)                                ! The 1 is for hard copy
1840  CALL Result(Av1(*),X(*),H)
1850  OFF KEY 9
1860 Gauss: OFF KEY 2                                 !KEY 1 OPTION IS STILL VALID
1870        OFF KEY 8
1880  ON KEY 1 LABEL "    FILTER   " GOTO 1600 ! ALLOWS ONE TO SMOOTH OLD DATA
1890                                           ! WHEN REVIEWING REDUCED FILES
1891  Old=1 ! THIS ALLOWS FILTERING EVEN AFTER ENTERING GRAPHICS MODE, THE
1892       ! DIODE COORDINATES AREN'T NEEDED ANYMORE *SEE LINES NEAR CALL FILTER
1900        PRINT CHR$(12)
1910  !Av2 Array is Normalized BUT  Av1(*) is Still Saved For Re-work if Needed
1920  MAT Av2= Av1   ! TO BEGIN WITH THE ARRAY IS ASSUMED TO BE NORMALIZED
1930                 ! AND THE USER CHANGES THIS WITH INTERACTIVE GRAPHICS
1940                 ! IN THE SUBROUTINE "Compare"
1950  P1$="FILTERED VOLTAGE    "
1960  P2$="THETA (rad)"                                       !STRINGS FOR PLOTS
1970  P3$="INTENSITY vs.THETA"
1980  P4$="CURVE FIT RESULTS"
1990  M5=.070                                                !SET UP VALUES
2000  Xt=.005                                                 !FOR PLOTS
2010  Yt=.1
2020  Xm=2
2030  Ym=2
2031  Xx=.02
2040  CALL Plot(Av1(*))
2050  CALL Result(Av1(*),T1(*),H)        !PLOT OF NORMALIZED INTENSITY vs. THETA
2060  GSTORE Graf(*)                     ! SAVES THE SCREEN IMAGE
2070  CALL Compare(Av1(*),H,M,M1,Graf(*))
2080   GRAPHICS OFF
2090   ON KEY 4 LABEL "OTHER  ARRAY" GOTO Choose
2100   ON KEY 5 LABEL " TWO-ANGLE" GOTO Buchele
2120   ON KEY 6 LABEL "STORE DATA" GOTO Storedata
2130   ON KEY 7 LABEL "   QUIT   " GOTO Quit
2140   CALL Menue1                                  ! PRINTS OPTIONS ON THE SCREEN
2150   GOTO Standby
2160 Buchele:  !
2170   CALL Twoangle
2180   CALL Menue1
2190   GOTO Standby
2200 Storedata:!
2210   CALL Store
2220   CALL Menue1
2230   GOTO Standby
2240 Quit:  !
2250  END
2260       SUB Average(J,Scans(*),Y(*),Av(*))  !AVERAGES SELECTED SCANS
2270       MAT Av= (0)              !INITIALIZES THE ARRAY LOCAL TO THIS ROUTINE
2280            FOR I=1 TO J STEP 1
2290            K=(Scans(I)-1)*1024+1           ! THIS COUNTER IS THE BEGINNING
2300            L=Scans(I)*1024                 ! AND THIS ONE THE END OF BLOCKS
2310                 FOR I1=K TO L              ! OF 1024 IN THE OVERALL DATA
```

```
2320                I2=I1-K+1                  ! THIS COUNTER IS ALWAYS BETWEEN
2330                Av(I2)=Av(I2)+Y(I1)        ! 1 AND 1024
2340                NEXT I1
2350           NEXT I
2360      MAT Av= Av/(J)
2370      SUBEND
2380 SUB Dataplot(B,Y(*),H)                    !B IS 4 OR 8(THE NUMBER OF SCANS)
2390 COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx
2400 LDIR 0
2410 LORG 4
2420      FOR J=1 TO B                         !EACH SCAN
2430      MOVE 500+J*50,M7-.05               ! SEE NEXT LINE
2440      LABEL J;                   ! HELPS KEEP TRACK OF EACH SCAN AS IT APPEARS
2450      LINE TYPE 1
2460      K=(J-1)*1024+1                       !BEGINNING OF EACH SCAN AND
2470      L=J*1024                             !THE END WITHIN THE TOTAL BLOCK
2480      MOVE 1,Y(K)                          ! MOVE TO THE FIRST POINT
2490           FOR I=K TO L STEP H
2500           X=I-K+1                       ! THIS GIVES 1 TO 1024 FOR ABSCISSA
2510           PLOT X,Y(I)
2520           NEXT I
2530      NEXT J
2540      PENUP
2541      M8=0
2550 SUBEND
2560     SUB Result(Iav(*),D(*),H)             !THE AVERAGE INTENSITY IS PLOTTED
2570     CLIP ON
2580     MOVE D(1),Iav(1)
2590          FOR I=1 TO 1024 STEP H
2600          DRAW D(I),Iav(I)
2610          NEXT I
2620          PENUP
2630     SUBEND
2631 Snlt:  !
2640 SUB Plot(Y(*),OPTIONAL Hard)             !IF THE OPTIONAL(Hard)IS RECEIVED
2650 COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx            !THE FIGURE GOES TO THE PLOTTER
2660 COM /Plots/ P1$[20],P2$[20],P3$[20],P4$[20]
2670 M7=MAX(Y(*))*1.1                          ! A SCALING VARIABLE
2680 M6=.1*M7                                 ! ANOTHER SCALING VARIABLE
2700 GINIT                                !GINIT IS JUST GOOD PRACTICE SO YOU KNOW
2710                                      !WHERE YOU ARE BEGINNING
2720 SELECT NPAR                         !THIS DETECTS IF THE HARD COPY IS DESIRED
2730 CASE 1                              !IT COULD BE DONE WITH IF THEN LOGIC
2740     PLOTTER IS 3,"INTERNAL"         !BUT IS PRESENTED FOR FAMILIARIZATION
2750 CASE 2                              !SINCE IT IS MORE POWERFUL IN COMPLEX
2760     PLOTTER IS 705,"HPGL"           !SITUATIONS
2770 END SELECT
2780 GRAPHICS ON                                        ! TO BE ABLE TO SEE THE PLOT
2790 CSIZE 5,.6
2800 DEG
2810 LDIR 0
```

```
2820 LORG 5
2830 MOVE 75,95
2840 LABEL USING "K";P4$
2850 MOVE 75,90
2860 LABEL P3$
2870 MOVE 75,20
2880 LABEL P2$
2890 LDIR 90
2900 MOVE 18,60
2910 LABEL P1$
2920 VIEWPORT 30,125,30,85                              ! SCREEN UNITS FOR MARGINS
2930 FRAME                                              ! DRAWS A BOX
2940 WINDOW Xx,M5,-M6,M7
2950 AXES Xt,M6,Xx,0,Xm,1,5
2960 LDIR 0
2970 CSIZE 3,.5
2980 LORG 8
2990 CLIP OFF
3000      FOR I=-M6 TO M7 STEP M7/10                    !NUMBER THE Y AXIS
3010      MOVE Xx,I
3020      LABEL USING "#,MD.DDDD";I
3030      NEXT I
3040 CSIZE 3,.6
3050 LDIR 90
3060      LORG 8
3070      FOR I=Xx TO M5 STEP Xt                         !NUMBER THE X AXIS
3080      MOVE I,-M6
3090      LABEL USING "#,K";I
3100      NEXT I
3110      PENUP
3120 SUBEND
3130     SUB Compare(Av1(*),H,M,M1,INTEGER Graf(*))
3140     COM /Gauss/ T1(*),L
3150     COM /Hrdgaus/ Av2(*)
3160     COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx
3201 Poot:  !
3202     PRINT " INPUT REFERENCE ANGLE  "
3203     INPUT Tt
3205     FOR N=1 TO 1024 STEP 1
3206     IF T1(N))=Tt THEN 3208
3207     NEXT N
3208     It=0
3209     FOR I=N-5 TO N+5
3210     It=It+Av1(I)
3211     NEXT I
3212     A1=It/11
3220          OFF KEY                             !GETS RID OF ALL LABELS ON KEYS
3230          ON KEY 3 LABEL "MENUE" GOTO 4160
3240          PLOTTER IS 3,"INTERNAL"       ! IN CASE A HARD COPY WAS JUST MADE
```

```
3250          Hard=0                        ! (0) SO ONE DOESN'T EXIT TOO SOON
3260          Centerline=1                     ! THE INITIAL NORMALIZING VALUE
3270          D=10.                 ! INITIAL PATICLE MEAN DIAMETER IN MICRONS
3280 Change:  CSIZE 4,.6
3290          PRINT USING "//////"
3300          PRINT "                                        STAND BY FOR CURVE"
3310          MOVE 0,1
3320          CLIP ON
3331          DIM T(1:1024)
3340          FOR I=1 TO 1024 STEP H
3350          T(I)=A1*EXP(-D^2*((T1(I)^2-Tt^2)*(((M1*.57*PI)/L)^2)))
3370          DRAW T1(I),T(I)
3375          IF (T1(I)*((PI*D*M1)/L))>3.0 THEN 3440
3380          NEXT I
3440          PENUP
3450      IF Hard THEN 3550           !EXITS ROUTINE IF A HARD COPY WAS JUST MADE
3460      PRINT USING "/////////"
3470      PRINT "                          USE THE KNOB TO VARY THE PARTICLE
SIZE"
3480      PRINT "                               OR HIT KEY # 6 FOR HARD COPY"
3490      PRINT " "
3500      PRINT "                                    KEY # 9 ALLOWS YOU TO"
3510      PRINT "                                    SELECT NEW REF ANGLE"
3520      PRINT " "
3530      PRINT "                                   HIT KEY # 3 TO GET OUT"
3540      PRINT USING "//////"
3541      OFF KEY 0
3550      ON KEY 6 LABEL "HARD COPY" GOTO Hardgauss
3560      ON KEY 9 LABEL "NORMALIZE" GOTO Poot
3570      ON KNOB .05 GOTO Pulse                !(.05) IS TIME INTERVAL IN WHICH
3580 Wait:  GOTO Wait                           ! PULSES FROM THE KNOB ARE
3590 Pulse: PRINT USING "@"                     ! COUNTED AND THIS NUMBER IS
3600         Strng1$="Mean Diameter "           ! USED BY THE INTERRACTIVE
3610         Strng2$=" Microns"                 ! GRAPHICS TO VARY THE PARTICLE
3620      Count=KNOBX                           ! SIZE AND PLOT THE ASSOCIATED
3630      D=DROUND(D+Count/15,2)                ! GAUSSIAN APPROXIMATIONS OF
3640      GLOAD Graf(*)                         ! SCATTERING PROFILES
3650      LDIR 0
3660      LORG 8
3670      MOVE M5,.8*M7
3680      LABEL Strng1$&VAL$(D)&Strng2$
3690      GOTO Change
3700 Hardgauss:!
3710      PRINT "                                          PREPARE the PLOTTER"
3720      PRINT "                                          PRESS CONTINUE for"
3730      PRINT "                                              HARD COPY"
3740      PAUSE
3750      Hard=1                       ! SO THAT SUBEXIT OCCURS AFTER HARD COPY
3760      CALL Plot(Av2(*),1)          ! 1**HARD COPY
```

```
3770     CALL Result(Av2(*),T1(*),H)
3780     PRINT USING "@"
3790     LORG 8
3800     MOVE M5,.8*M7
3810     LDIR 0
3820     LABEL Strng1$&VAL$(D)&Strng2$
3840     GOTO Change
4160 Subexit:    !
4170     SUBEND
4180      SUB Menuel
4190        PRINT USING "@"
4200        PRINT "                         YOU CAN RE-NORMALIZE"
4210        PRINT "**************************************************************"
4220        PRINT "                          YOU CAN RE-AVERAGE (New Data Only)"
4230        PRINT "**************************************************************"
4240        PRINT "                    PRESS KEY # 4 TO LOOK AT OTHER DATA"
4250        PRINT "                               OLD OR NEW "
4260        PRINT "                            MOTOR / EXHAUST"
4270        PRINT "**************************************************************"
4280        PRINT "                            PRESS KEY # 5 "
4290        PRINT "                      FOR THE ' TWO-ANGLE ' METHOD"
4300        PRINT "                          OF PARTICLE SIZING"
4310        PRINT "**************************************************************"
4320        PRINT "              TO STORE THE REDUCED DATA PRESS KEY # 6      "
4330        PRINT "**************************************************************"
4340        PRINT "                 TO END THIS SESSION PRESS KEY # 7"
4350      SUBEND
4360      SUB Display1(Old)
4370  PRINT "                        TO REDUCE NEW DATA PRESS KEY # 1"
4380  PRINT ""
4390  PRINT "                 TO REVIEW PREVIOUSLY REDUCED DATA PRESS KEY # 2"
4400  PRINT "   "
4410  ON KEY 1 LABEL "  NEW DATA" GOTO New
4420  ON KEY 2 LABEL "  OLD DATA" GOTO Review
4430 Wait: GOTO Wait
4440 New: PRINT CHR$(12)
4450  PRINT "           PUT THE DISK IN THE LEFT DRIVE IF IT IS NOT ALREADY"
4460  PRINT ""
4470  PRINT "              ENTER THE NAMES OF THE FIRST AND SECOND FILES."
4480  PRINT ""
4490  PRINT "               EACH FILE HAS  DATA FROM BOTH DIODE ARRAYS."
4500  PRINT ""
4510  PRINT "           FIRST IS NO-PARTICLES & NEXT IS PARTICLES ----D1$,D2$"
4520  PRINT ""
4530  Old=0
4540  SUBEXIT
4550 Review:  Old=1     !THIS VARIABLE IS PASSED TO THE MAIN PROGRAM TO INDICATE
4560                    !THAT THE DATA TO BE READ IS ONE (1) SCAN AND THAT
4570                    !THE AVERAGING ROUTINES WILL NOT BE USED
```

```
4580          SUBEND
4590 SUB Readata
4600 COM /Readata/ B,P,H,Q3$[20],Q4$[20],Zz$[20],Y1(*) BUFFER,Y2(*) BUFFER
4610 Xyz=1                                                 ! FILE POINTER VARIABLE
4620 B=8                                          ! NUMBER OF SCANS IN MOTOR DATA
4630 R1=65536                                     !NUMBER OF BYTES   OF MOTOR DATA
4640 IF P=2 THEN Xyz=4097                    !RECORD # WHERE 4 SCANS DATA BEGINS
4650 IF P=2 THEN R1=32768                     !NUMBER OF BYTES   OF 4 SCAN DATA
4660 IF P=2 THEN B=4                              !NUMBER OF SCANS
4670 PRINT " "
4680 PRINT "                READING DATA FROM FILE ON DISK"
4690       ASSIGN @Disk1 TO Q3$&Zz$
4700       ASSIGN @Disk2 TO Q4$&Zz$                                  !OPEN I/O PATHS
4710       ASSIGN @Buff1 TO BUFFER Y1(*)
4720       ASSIGN @Buff2 TO BUFFER Y2(*)
4730       CONTROL @Disk1,5;Xyz
4740       TRANSFER @Disk1 TO @Buff1;COUNT R1               !READS NO-PARTICLE DATA
4750       WAIT FOR EOT @Disk1                          ! NOT AN OVERLAPPING TRANSFER
4760       CONTROL @Disk2,5;Xyz                         !Xyz SETS DISK FILE POINTER TO
4770                                                    !EITHER MOTOR OR EXHAUST DATA
4780       TRANSFER @Disk2 TO @Buff2;COUNT R1                    !READS PARTICLE DATA
4790       WAIT FOR EOT @Disk2
4800       ASSIGN @Disk1 TO *
4810       ASSIGN @Disk2 TO *                            !JUST GOOD PRACTICE TO CLOSE
4820       ASSIGN @Buff1 TO *                            !I/O PATHS
4830       ASSIGN @Buff2 TO *
4840 SUBEND
4850 SUB Plot2(E,D(*),X)
4860     DIM Title1$[25],Theta$[20]
4870     GINIT
4880     IF X=1 THEN PLOTTER IS 705,"HPGL"
4890     DEG                                             !DEGREES for LABEL DIRECTION
4900     GRAPHICS ON
4910     VIEWPORT 35,125,35,85
4920     Max=10*INT((MAX(D(*))+10)/10)
4930     WINDOW D(1,2),D(E,2),0,Max
4940     G=(D(E,2)-D(1,2))/(E-1)*4          !AN X GRID LINE EVERY 4th POINT
4950     F=(INT(E/4)-1)*4
4960     IF F=0 THEN F=4
4970     CLIP D(4,2)-G,D(F,2)+2*G,0,Max      !MAKES GRID UNIFORM
4980     GRID G,5,D(4,2)-G,0
4990     CLIP OFF
5000     LORG 8
5010     LDIR 90
5020     CSIZE 4,.5
5030     FOR I=4 TO E STEP 4                                 !PUTS NUMBERS ON X AXIS
5040          MOVE D(I,2),0
5050          LABEL USING ".DDDD";D(I,2)
5060     NEXT I
```

```
5070    LDIR 0
5080    LORG 9
5090    FOR I=10 TO Max STEP 10                               !NUMBER Y AXIS
5100         MOVE D(4,2)-G,I
5110         LABEL USING "#,K";I
5120    NEXT I
5130    CSIZE 6,.6
5140    Title$="TWO-ANGLE METHOD"
5150    Title1$="For Various Angle Ratios"                    !STRINGS FOR PLOTS
5160    Size$="SIZE  (microns)"
5170    Thta$="THETA  (rad)"
5180    Sub$="1"
5190    LDIR 90
5200    LORG 5
5210    B=D(4,2)-G-(D(E,2)-D(1,2))/10
5220    MOVE B,Max/2
5230    LABEL Size$
5240    LDIR 0
5250    A=(D(E,2)+D(1,2))/2
5260    MOVE A,-Max/4
5270    LABEL Thta$
5280    LORG 3
5290    MOVE A,-Max/4
5300    LABEL Sub$
5310    LORG 5
5320    MOVE A,Max*1.15
5330    LABEL Title$
5340    CSIZE 4.5
5350    MOVE A,Max*1.05
5360    LABEL Title1$
5370    PENUP
5380 SUBEND
5390 SUB Distribution(D(*),Tratio,E)
5400    LINE TYPE 1
5410    CLIP ON
5420    Tratio$=VAL$(Tratio)                                     ! ANGLE RATIO
5430    MOVE D(1,2),D(1,1)
5440    FOR I=1 TO E                          !THIS SUBROUTINE PLOTS THE
5450         DRAW D(I,2),D(I,1)               !PARTICLE SIZES DERIVED USING
5460    NEXT I                                !VARIOUS ANGLE RATIOS APPLIED
5470    LORG 4                                !TO THE DATA OVER A RANGE OF
5480    LINE TYPE 1                           !ANGLES
5490    CSIZE 4,.3
5500    MOVE D(I-1,2),D(I-1,1)+2
5510    LABEL Tratio$
5520    PENUP
5530 SUBEND
5540 SUB Twoangle
```

```
5550  !************************************************************
5560  !***************      SUBPROGRAM 'TWOANGLE'      ******************
5570  !***************       PARTICLE SIZING BY        ******************
5580  !***************       MEASURING THE RATIO       ******************
5590  !***************        OF INTENSITY AT          ******************
5600  !***************          TWO ANGLES             ******************
5610  !************************************************************
5620 OPTION BASE 1
5630 COM /Two/ Av1(1024),M,M1,F
5640 COM /Gauss/ T1(1024),L                    !THE GAUSS IS NOT USED HERE
5650                                                     !BUT THE COM BLOCK HAS THETA
5660 DIM D(200,2)                                        !AND WAVELENGTH
5670 PRINT CHR$(12)
5680 PRINT USING "///////"
5690 PRINT "     THIS SUBPROGRAM USES THE TWO-ANGLE METHOD DESCRIBED BY BUCHELE"
5700 PRINT " "
5710 PRINT "     TO CALCULATE PATICLE SIZE FOR VARIOUS ANGLE RATIOS AND ANGLES."
5720 PRINT " "
5730 PRINT "            IT IS HOPED THAT THE CURVES WHICH RESULT WILL SHOW "
5740 PRINT " "
5750 PRINT "                        WHICH SIZE IS THE MOST PROBABLE."
5760 PRINT " "
5770 PRINT "AFTER NOTING FROM THE RAW DATA WHICH ANGLES CONTAIN THE CENTER LOBE"
5780 PRINT ""
5790 PRINT "       ENTER*************THE SMALLEST USEABLE ANGLE,"
5800 PRINT "                          THE SMALLEST ANGLE RATIO,AND"
5810 PRINT "                        THE STEP SIZE BETWEEN ANGLE RAIOS"
5820 PRINT "                               YOU WISH TO EXPLORE"
5830 PRINT "     EXAMPLE*************       .012,1.2,.4"
5840 INPUT " ENTER              theta1,theta-ratio,theta-step",Q,A,B
5850     OFF KEY
5860     X=0                                            !GRAPH WILL APPEAR ON SCREEN
5870 Begin:                   !RUNNING CONTINUES HERE WHEN A HARD COPY IS DESIRED
5880          !Van De Hulst and Gumprech & Sleepevich explain that the change in
5890          !wavelength of the beam is accounted for by dividing by the index
5900          !of refraction of the medium. *********L=L/M1 **********
5910 C=(L/M1/.57/PI)^2          !-------------see page 15 of nasa tech paper 2156
5920 FOR N=1 TO 1024                         !to see this is a convenient constant
5930      IF Q<T1(N) THEN 5950                     !FINDS POSITION OF MINIMUN ANLGE
5940 NEXT N
5950 FOR Tratio=A TO 3 STEP B                            !VARIOUS ANGLE RATIOS
5960     FOR J=N TO 1010/Tratio STEP 10                  !SETS THE RANGE OF POSSIBLE
5970                                                     ! ANGLES (THETA 1)
5980          Thta1=T1(J)
5990          Thta2=T1(J*Tratio)                         ! THETA 2
6000          Deltatheta=Thta2^2-Thta1^2
6010          I1=0
6020          I2=0
```

```
6030          FOR I=J-5 TO J+5                      !THESE 2 LOOPS AVERAGE A FEW
6040               I1=I1+Avl(I)                     !INTENSITIES IN THE HOPE
6050          NEXT I                                !OF A STEADIER CALCULATION
6060               I1=I1/11
6070          FOR I=INT(J*Tratio-5) TO INT(J*Tratio+5)
6080               I2=I2+Avl(I)                     ! DONE HERE FOR THETA2 FOR
6090          NEXT I                                ! THE GIVEN ANGLE RATIO
6100               I2=I2/11
6110          E=(J-N)/10+1            !THIS IS A COUNTER FOR THE ARRAY CONTAINING
6120                                  !PARTICLE SIZE AND THETA1 FOR THE GIVEN
6130                                  !ANGLE RATIO
6140          IF I1<I2 OR I1=0 OR I2<=0 THEN D(E,1)=0 !ALLOWANCE FOR IF THE DATA
6150          IF I1<I2 OR I1=0 OR I2<=0 THEN GOTO Xcomp  !IS NOT WELL BEHAVED
6160          D(E,1)=SQR(-C/Deltatheta*LOG(I2/I1))           !TWO ANGLE METHOD
6170                                  !VALUE OF DIAMETER based on INTENSITY RATIO
6180                                  !For a given ANGLE RATIO and ANGLE THETA1
6190 Xcomp:   D(E,2)=Thta1
6200         Spar=PI*D(E,1)*M1/L      !THIS IS PI*D/LAMBDA  -- THE SIZE PARAMETER
6210         Tbar=Spar*Thta2                      !THETA BAR FOR THE LARGER ANGLE
6220         IF Tbar>4 THEN J=1010/Tratio         !THIS ENDS THE DO LOOP FOR THIS
6230         IF E=1 AND Tbar>3 THEN 6330          !ANGLE RATIO SINCE THE GAUSSIAN
6240  !the above line ends all calculation if      !IS NOT VALID WHEN Tbar > 3
6250  !the first element (E=1)failed the test
6260    NEXT J
6270                 !   FIRST TIME THROUGH-- D HAS THE MOST ELEMENTS IT WILL HAVE
6280                 !   SO SET UP THE GRAPH USING D's PRESENT PARAMETERS
6290 PRINT CHR$(12)
6300     IF Tratio=A THEN CALL Plot2(E,D(*),X)
6310     CALL Distribution(D(*),Tratio,E)
6320 NEXT Tratio
6330     ON KEY 2 LABEL "HARD COPY" GOTO Hard
6340     ON KEY 3 LABEL "MENUE " GOTO Subexit
6350 PRINT USING "/////"
6360 PRINT "                   YOU CAN GET A HARD COPY BY PRESSING KEY # 2"
6370 PRINT "                      OR EXIT THIS ROUTINE BY PRESSING KEY # 3"
6380 Standby:GOTO Standby
6390 Hard:X=1                                         !A VARIABLE TO CONTROL PLOTTER
6400       GOTO Begin
6410 Subexit: GINIT
6420           GRAPHICS OFF
6430 SUBEND
6440  SUB Shift
6450  COM /Readata/ B,P,H,Q3$[20],Q4$[20],Zz$[20],Y1(*) BUFFER,Y2(*) BUFFER
6460  DIM E(1:8192)
6470  PRINT CHR$(12)
6480  PRINT USING "///////"
6490  PRINT " RAW DATA IS BEING SHIFTED TO CORRECT FOR SMALL GAPS BETWEEN SCANS"
6500  PRINT ""
6510  PRINT "                  BE PATIENT, IT'S A LONG SET OF DO-LOOPS"
```

```
6520        !       THERE ARE SOME SMALL GAPS BETWEEN SCANS AND THIS SURROUTINE
6530        !       SHIFTS THE DATA SO THAT THE FIRST DIODE DATA POINT IS MOVED
6540        !       TO THE VERY BEGINNING OF ITS 1024 BLOCK IN THE OVERALL ARRAY
6550        !       .THE FIRST SET IS RIGHT ON, THE NEXT IS ONE OFF,THE THIRD IS
6560        !       TWO OFF ,,SO FORTH.  THIS MAY NOT MATTER WITH OUR RESOLUTION
6570        !       AND IS PROBABLY DUE TO THE MEMORY CARD CYCLING AT THE END OF
6580        !       SOME SCANS. SEE THE CIRCUIT TIMING DIAGRAM IN THE THESIS.
6590      SELECT B
6600      CASE 4                     !EXHAUST DATA HAS 4 SCANS
6610          M=3
6620      CASE 8                     !MOTOR DATA HAS 8 SCANS
6630          M=7
6640      END SELECT
6650   FOR K=1 TO 2
6660   IF K=1 THEN MAT E= Y1         !OPPERATES ON NO-PARTICLE AND PARTICLE SETS
6670   IF K=2 THEN MAT E= Y2
6680          FOR J=0 TO M
6690          IF M=7 AND J<=3 THEN 6800  !One 4096 Block Doesn't Need Shifting
6700              FOR I=(J)*1024+1 TO (J+1)*1024            !BLOCKS OF 1024
6710                  IF M=3 THEN L=I+J       !Array B Has the worst
6720                                          !Problem With Shifting Data
6730                  IF M=7 THEN L=I+1       !Array D is Allways off by one
6740                  IF L>(J+1)*1024 THEN L=(J+1)*1024
6750             !JUST TO AVOID PROGRAMMING ERROR AT THE END OF THE ARRAY
6760                  E(I)=E(L)                 !THIS SHIFTS THE DATA
6770                                            !DEPENDING ON 'L',ARRIVED AT
6780                                            !BY OBSERVING RAW DATA
6790              NEXT I
6800          NEXT J
6810      IF K=1 THEN MAT Y1= E
6820      IF K=2 THEN MAT Y2= E
6830  NEXT K
6840  SUBEND
6850  SUB Store    ! THE LARGE ARRAY CONTAINING MULTIPLE SCANS HAS BEEN REDUCED
6860               ! TO A MEAN SCATTERING PROFILE BY AVERAGING AND FILTERING. IF
6870               ! YOU FEEL THAT STORING THIS DATA IS NECESSARY THIS ROUTINE
6880               ! DOES IT. IT SAVES DISK SPACE TO STORE THE RESULTS THEN
6890               ! ELIMINATE THE RAW DATA IF YOU FEEL CONFIDENT THAT THE
6900               ! REDUCTION IS THE BEST THAT CAN BE.  IN OTHER WORDS,
6910               ! DO NOT PURGE A RAW DATA FILE UNLESS YOU ARE ABSOLUTELY SURE
6920               ! YOU WON'T WANT TO REDUCE IT AGAIN.
6930  COM /Hrdgaus/ Av2(*)                          !Av2(*) IS THE REDUCED DATA
6940  DIM Data(1:1024) BUFFER                   !BUFFER USED TO TRANSFER TO DISK
6950  MAT Data= Av2
6960  PRINT CHR$(12)
6970  PRINT USING "//////"
6980  PRINT "    A  SUGGESTED METHOD OF NAMING REDUCED DATA FILES IS AS FOLLOWS"
6990  PRINT "  M-------MOTOR BEAM"
7000  PRINT "  X-------EXHAUST BEAM"
```

```
7010  PRINT "  C-------CALIBRATION , IF NO 'C' THEN AN ACTUAL FIRING IS ASSUMED"
7020  PRINT "  G-------GLASS BEADS "
7030  PRINT "                    IF NO 'C' THEN 'G' STANDS FOR 'GAP' PROPELLANT"
7040  PRINT "  A-------ALUMINUM OXIDE"
7050  PRINT "  PPP-----CHAMBER PRESSURE FOR RUN OR OTHER....(NOZZLE TYPE)"
7060  PRINT "          PARTICLE SIZE FOR CALIBRATION"
7070  PRINT "  MMDD----MONTH,DAY OF RUN OR CALIBRATION"
7080  PRINT ""
7090  PRINT "                          EXAMPLE:    MCA125JN12"
7100  PRINT ""
7110  PRINT "  MOTOR BEAM CALIBRATION USING ALUMINUM OXIDE FROM 1 TO 25 MICRONS"
7120  PRINT "  ON JUNE 12"
7130  PRINT "                          EXAMPLE:    XG550AU10"
7140  PRINT ""
7150  PRINT "  EXHAUST BEAM DATA FOR GAP PROPELLANT AT 550 psi ON AUGUST 10"
7160  PRINT "              PLACE A DISK IN THE RIGHT HAND DRIVE"
7170  PRINT "  ENTER THE FILENAME YOU WISH TO USE FOR THIS REDUCED DATA"
7180  INPUT A$
7190  CREATE BDAT A$,512,16
7200  ASSIGN @Disk TO A$
7210  ASSIGN @Buff TO BUFFER Data(*)
7220  CONTROL @Buff,3;1,8192,1                         !BUFFER IS FULL
7230  TRANSFER @Buff TO @Disk;COUNT 8192
7240  WAIT FOR EOT @Disk
7250  ASSIGN @Buff TO *
7260  ASSIGN @Disk TO *
7270  SUBEND
7280  SUB Review(Av1(*))
7290  DIM Data(1:1024) BUFFER
7300  PRINT " EACH REDUCED FILE CONTAINS ONE SCAN ONLY.  YOU MUST KNOW IF IT"
7310  PRINT "      IS EXHAUST , MOTOR CAVITY , OR CALIBRATION DATA."
7320  PRINT ""
7330  PRINT " THE DISK WITH THE REDUCED FILE SHOULD BE IN THE RIGHT-HAND DRIVE"
7340  PRINT ""
7350  PRINT "            ENTER THE FILENAME OF THE REDUCED DATA"
7360  PRINT "                         TO BE REVIEWED"
7370  PRINT ""
7380  INPUT A$
7390  ASSIGN @Disk TO A$
7400  ASSIGN @Buff TO BUFFER Data(*)
7410  CONTROL @Disk,5;1
7420  CONTROL @Buff,3;1,0,1                       !THIS IS AN EMPTY BUFFER
7430  TRANSFER @Disk TO @Buff;COUNT 8192          !1024*8=NUMBER OF BYTES
7440  WAIT FOR EOT @Disk
7450  ASSIGN @Disk TO *
7460  ASSIGN @Buff TO *
7470  MAT Av1= Data
7480  SUBEND
7490  SUB Filter(A(*),Fil)
```

```
7500  DIM E(1:1024)
7510  PRINT CHR$(12)
7520  PRINT USING "////////"
7530  PRINT "                                    FILTERING THE SCATTERING PROFILE"
7540       FOR J=1 TO Fil
7550                 FOR I=1 TO 1014
7560                       B=I+1              !THIS IS A Symetric Moving Average
7570                       C=I+2              !TYPE OF DIGITAL FILTER. EACH
7580                       D=I+3              !DATA POINT IS EQUALLY WEIGHTED
7590                       F=I+4              !IN THIS CASE BUT THIS CAN BE
7600                       G=I+5              !CHANGED IF ONE DETERMINES THAT
7610                       H=I+6              !FEWER POINTS WITH UNEQUAL WEIGHTS
7620                       K=I+7              !WOULD BE FASTER OR GIVE BETTER
7630                       L=I+8              !RESULTS.  THIS TYPE OF FILTER WAS
7640                       N=I+9              !USED SINCE IT INTRODUCES NO PHASE
7650                       P=I+10             !LAG        (Angular Resolution).
7660   E(G)=(A(I)+A(B)+A(C)+A(D)+A(F)+A(G)+A(H)+A(K)+A(L)+A(N)+A(P))/11
7670                 NEXT I
7680             MAT A= F
7690       NEXT J
7700  SUBEND
```

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